Essays on Arbitrage and Market Liquidity

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ESSAYS ON ARBITRAGE AND MARKET LIQUIDITY

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Davide Tomio

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The PhD School in Economics and Management

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Essays on Arbitrage and Market Liquidity

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"The PhD School in Economics and Management is an active national and international research environment at CBS for research degree students who deal with economics and management at business, industry and country level in a theoretical and empirical manner".

Preface

This dissertation includes three essays I worked on during my Ph.D. studies at the Copenhagen Business School. While the papers overlap in their goal of understanding what drives market liquidity and the mispricing between securities connected by arbitrage, they are self-contained and can be read independently.

Working on this dissertation over the past years, I benefited tremendously from the guidance and counsel of my advisers at CBS, Lasse Heje Pedersen and Søren Hvidkjær. They provided me with invaluable lessons and learning experiences and truly prepared me to tackle the academic job market. I am deeply indebted to my co-authors Marti G. Subrahmanyam, Loriana Pelizzon, and Jun Uno for their patience, support, kindness, and camaraderie. Their tireless will to show me the ropes of financial academia and their skills in investigating varied research questions are examples of mentorship and scholarship.

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Finally, this endeavor would have been overwhelming without the affection and friendship of many. I am thankful for the unwavering support and love of Troels, my family, and friends. Fellow Ph.D. students and faculty at CBS have contributed to making the last few years instructive and enjoyable.

Davide Tomio
New York City, April 2017

Summary

Summary in English

Sovereign Credit Risk, Liquidity, and ECB Intervention: *Deus ex Machina*?

With Loriana Pelizzon, Marti G. Subrahmanyam, and Jun Uno

The first essay investigates how credit risk, the risk that a bond issuer will default, affects bond market liquidity. Specifically, we depart from the current literature in that we analyze the direct and indirect channels through which credit risk affects market liquidity, rather than determining whether both are priced in the bond. We focus on the Italian sovereign bond market, which allows us to determine how central bank interventions affect the sensitivity of the liquidity provision by market makers to default risk.

We motivate our empirical analysis with a simple model of a risk averse market maker, holding an inventory of a risky asset and setting her optimal marginal quotes (and, therefore, the optimal bid-ask spread), in the presence of margin constraints and borrowing costs. The margins, set by a clearing house, depend on the risk of the asset, as measured by the CDS spread, and the actions of the central bank. The CDS market is fundamental to the market maker's and the clearing house's decisions, since it is from the CDS market that they deduce the future volatility of the asset return. In addition, the market maker can pledge her assets at the central bank to finance her positions at rates influenced by the central bank's actions. The model provides several empirical predictions that we test in the empirical section of the paper.

First, we test the empirical prediction that the relation between the credit risk of a sovereign bond and its liquidity is statistically significant and, specifically, that the credit risk, as measured by the CDS spread, leads the liquidity, and not the other way around. Second, we examine whether the relation between credit risk and market liquidity is conditional on the level of the CDS spread. We let the data identify the presence of such a CDS threshold effect, and find that the relation between market liquidity and credit risk is different, depending on whether the Italian CDS spread is below or above 500 bp. We interpret this finding, together with a change in the margins for bonds, in light of the predictions made by Brunnermeier and Pedersen (2009). Third, we analyze the impact of ECB intervention on the relation between credit risk and liquidity. Our test for an endogenous structural break indicates that, when the ECB allotted the funds of the LTRO program, the relation between the two variables changes significantly. Thereafter, during 2012, after the large amount of funding liquidity from the LTRO program has become available to market makers and market participants, changes in market liquidity respond to changes in credit risk with a significantly lower intensity.

Arbitraging Liquidity

The second essay investigates the effect that arbitrageurs have on the co-movement between the market liquidity of assets connected by an arbitrage relationship. In this paper, I argue that the level of arbitrage activity, defined by profiting from divergences of prices of identical securities across markets, contributes to the liquidity convergence between markets. By detailing the trading strategies available to an arbitrageur, I show in a simple trading framework how the market and limit orders submitted by arbitrageurs create co-movement across markets and lead to the convergence of bid prices, ask prices, and bid-ask spreads.

I test this theoretical prediction empirically and show that the intensity of arbitrage activity contributes positively to the co-movement of market liquidity between securities linked by arbitrage. To do so, I employ high-frequency data for Canadian stocks cross-listed in the United States, to verify my hypotheses. Finally, I show the generality of my results by considering an alternative arbitrage trade, and showing that the liquidity commonality across stocks and corporate bonds is increasing in the amount of capital structure arbitrage activity.

Employing data on the quotes of 125 Canadian stocks that are cross-listed in the United States, I determine, during each of the more than six million trading seconds of 2013, whether an arbitrage opportunity was available between the stock listed in the United States and its counterpart traded in Canada. I show that the co-movement between liquidity changes for securities connected by arbitrage is much larger for the sub-sample with few arbitrage opportunities, i.e., those with high arbitrage activity. For example, the correlation in liquidity changes over a one-minute interval is 7% for stock-days with a large number of arbitrage opportunities, and 25% for observations with a small number of arbitrage opportunities. Finally, I extend the previous finding outside the realm of stock markets alone, considering a different arbitrage trade, using capital structure arbitrage. I show that the commonality in liquidity between the bond and the stock market is higher when arbitrageurs are active, which supports the generality of my findings.

Limits to Arbitrage in Sovereign Bonds

With Loriana Pelizzon, Marti G. Subrahmanyam, and Jun Uno

Commonality of liquidity refers to the linkages between liquidity across assets through common market-wide factors. We term the phenomenon of the transmission of liquidity between assets linked by arbitrage as liquidity discovery, describing the process by which information is reflected in market liquidity, in a manner analogous to the concept of price discovery, which relates to the reflection of information in prices. This third essay investigates the relationship between liquidity discovery and price discovery.

We use millisecond-level data from the cash and futures markets in the context of the Italian sovereign bond markets during the recent Euro-zone sovereign bond crisis and find that: (i) even though the futures market leads the cash market in price discovery, the cash market leads the futures market in liquidity discovery, i.e., the willingness of market makers to trade (measured by market depth and bid-ask spread), and (ii) the liquidity in the cash market, and not in the futures market, has a significant impact on the basis between the price of the futures contract and that of the bond.

In our investigation, we are mindful of the impact of ECB interventions on the linkage between these two markets in terms of price and liquidity. We shows that the introduction of the LTRO program, by providing liquidity to the banks, restored liquidity in both the futures and the cash bond market, drove the basis to zero and quickened the relationship between the illiquidity in the cash and future markets. The SMP intervention had the opposite result, widening the mispricing between the securities connected by arbitrage, removing liquidity from the bond market, thus finally affecting the liquidity of the futures market.

Summary in Danish

Sovereign Credit Risk, Liquidity, and ECB Intervention: *Deus ex Machina*?

Sammen med Loriana Pelizzon, Marti G. Subrahmanyam og Jun Uno

Det første essay undersøger hvordan kreditrisiko, det vil sige risikoen for, at en obligationsudsteder misligeholder sine betalingsforpligtelser, påvirker likviditeten i obligaionsmarkedet. Vi adskiller os fra den nuværende litteratur ved at analysere de direkte og indirekte kanaler, gennem hvilke kreditrisikoen påvirker markedslikviditeten, i stedet for at afgøre, om begge dele afspejles i obligationens pris. Vi fokuserer på det italienske statsobligationsmarked, hvilket gør det muligt for os at fastslå, hvordan centralbanksinterventioner påvirker følsomheden af prisstillernes likviditetsformidling over for fallitrisiko.

Vi motiverer vores empiriske analyse med en simpel model, hvor en risikoavers prisstiller med en beholdning af risikofyldte aktiver sætter sine optimale marginale priser (og dermed det optimale bid-ask-spread) under tilstedeværelse af marginberænsninger og låneomkostninger. Marginerne, som fastsættes af clearing-huset, afhænger af aktivets risiko målt ved CDS-spreadet og centralbankens handlinger. CDS-markedet er fundamentalt for pristillerens og clearings-husets beslutninger, fordi det er fra CDS-markedet, at de udleder den fremtidige volatilitet af aktivafkastet. Ydermere kan prisstilleren give sine aktiver til centralbanken for at finansere sine positioner til renter påvirket af centralbankens handlinger. Modellen giver adskillige empiriske forudsigelser, som vi afprøver i den empiriske del af artiklen.

Først afprøver vi den empiriske forudsiglese, at relationen mellem kreditrisikoen og likviditeten af en statsobligation er statistisk signifikant, og specifikt at kreditrisikoen målt ved CDS-spreadet leder likviditeten og ikke omvendt. Dernæst undersøger vi, om forholdet mellem kreditrisiko og markedslikviditet er betinget af niveauet af CDS-spreadet. Vi lader dataene identificere tilstedeværelsen af en sådan CDS-grænse-effekt og viser, at forholdet mellem markedslikviditet og kreditrisiko er anderledes afhængigt af, om det italienske CDS-spread er under eller over 500bp. Vi tolker dette resultat, samt en ændring i marginerne for obligationer, i lyset af forudsigelserne fremsat af Brunnermeier and Pedersen (2009). Til sidst analyserer vi effekten af ECB-indgreb på forholdet mellem kreditrisiko og likviditet. Vores test for et endogent, strukturelt brud indikerer, at da ECB tildelte finansiering gennem LTRO-programmet, ændrede forholdet mellem de to variable sig signifikant. Derefter, i løbet af 2012, efter den store mængde af finansieringslikviditet fra LTRO-programmet er blevet tilgængeligt for prisstillerne og markedsdeltagerne, responderer ændringer i markedslikviditet på ændringer i kreditrisiko med en signifikant lavere intensitet.

Arbitraging Liquidity

Det andet essay undersøger, hvilken effekt arbitrageurs har, på hvordan markedslikviditeten af aktiver forbundet ved et arbitrage-forhold bevæger sig i forhold til hinanden. I denne artikel argumenterer jeg for, at niveauet af arbitrage-aktivitet, der er defineret ved gevinsttagning på baggrund af afvigelser i priser af to identiske aktiver på tværs af markeder, bidrager til likviditetskonvergens mellem markeder. Ved at udspecificere detaljerne for handelsstrategierne, som er tilgængelige for en arbitrageur, viser jeg i et simpelt handelssystem, hvordan markeds- og limit-ordrer afgivet af arbitrageurs skaber en fælles bevægelse på tværs af markeder og leder til konvergens af bid-priser, ask-priser og bid-ask-spread.

Jeg afprøver den teoretiske forudsigelse empirisk og viser, at intensiteten af arbitrage-aktivitet bidrager positivt til den fælles bevægelse af markedslikviditeten for aktiver forbundet gennem arbitrage ved at se på canadiske aktier, der også handler på amerikanske børser.

Ved at anvende data på de stillede priser for 125 canadiske aktier, der også handler på amerikanske børser, afgør jeg, om en arbitragemulighed var tilgængelig mellem aktien handlet på en amerikansk børs og dens modpart handlet i Canada i løbet af hver af de mere end 6 millioner handelssekunder i 2013. Jeg viser, at den fælles bevægelse mellem likviditetsændringer for aktiver forbundet ved arbitrage er langt større for den delmængde med få arbitragemuligheder, det vil sige dem med høj arbitrageaktivitet. For eksempel er korrelationen i livkiditetsændringer for et et-minuts-interval 7% for aktie-dage med et højt antal af arbitragemuligheder og 25% for observationer med et lavt antal af arbitragemuligheder. Endelig udvider jeg det foregående resultat til også at strække sig ud over aktiemarkederne ved at undersøge en anden arbitragehandel. Jeg fokuserer her på kapitalstrukturarbitrage. Jeg viser, at ensartetheden i likviditeten mellem obligations- og aktiemarkedet er højere, når arbitrageurs er aktive, hvilket underbygger almenheden af mine resultater.

Limits to Arbitrage in Sovereign Bonds

Sammen med Loriana Pelizzon, Marti G. Subrahmanyam og Jun Uno

Ensartethed i likviditet henviser til forbindelserne mellem likviditet på tværs af aktiver gennem fælles, markedsomspændende faktorer. Begrebet af transmission af likviditet mellem aktiver forbundet ved arbitrage kalder vi likviditetsopdagelse, analogt til konceptet prisopdagelse, som beskriver hvordan priser afhænger af information. Denne artikel undersøger forholdet mellem likviditetsopdagelse og prisopdagelse.

Vi bruger data på millisekundsniveau fra obligations- og futuresmarkederne for italienske statsobligationsmarkeder i løbet af den nylige Euro-zone-statsobligations-krise og viser at: (i) selvom futuresmarkedet leder obligationsmarkedet i prisopdagelse, leder obligationsmarkedet futuresmarkedet i likviditetsopdagelse, det vil sige prisstillernes villighed til at handle (målt ved markedsdybde og bid-ask-spread), og (ii) likviditeten i obligationsmarkedet, og ikke i futuresmarkedet, har en signifikant effekt på basisen mellem prisen på futureskontrakten og obligationsprisen.

I vores undersøgelse er vi opmærksomme på effekten af ECB-indgreb på forbindelsen mellem disse to markeder med hensyn til pris og likviditet. Vi viser, at indførelsen af LTRO-programmet, der formidlede likviditet til bankerne, genoprettede likviditeten i både futures- og obligationsmarkedet, drev basisen mod nul og forstærkede forholdet mellem obligations- og futuresmarkederne. SMP-indgrebet havde det modsatte resultat og forøgede prisafvigelserne mellem aktiver forbundet ved arbitrage. Dette fjernede likviditet fra obligationsmarkedet for derigennem endeligt at påvirke likviditeten af futuresmarkedet.

Contents

Introduction

This dissertation consists of three essays aimed at understanding what drives market liquidity and the mispricing between securities connected by arbitrage. The first essay (co-authored with Loriana Pelizzon, Marti G. Subrahmanyam, and Jun Uno) sets the stage by investigating how credit risk affects bond market liquidity. We address theoretically and empirically the direct and indirect channels through which default risk affects the liquidity provision of market makers in a sovereign bond market. The second essays considers the market liquidity of an asset together with that of a second asset, to which the first is connected by an arbitrage relationship. I show that the liquidity of the two assets co-moves more when arbitrageurs are trading in both markets, taking advantage of the relative mispricing between the two securities. The third essay considers how the liquidity spills over between two securities connected by arbitrage. That is, in the last chapter (co-authored with Loriana Pelizzon, Marti G. Subrahmanyam, and Jun Uno), we focus on the propagation of a liquidity shock and show how a large buying pressure exerted by an exceptional trader (a central bank) affects the pricing relation between two securities and how the illiquidity arising in one market is transferred to the other.

In the first essay, we determine the drivers of market liquidity for the Italian sovereign bond market and analyze the relation between market liquidity and credit risk and how this relation changed thanks to the ECB interventions. We motivate our analysis by developing a simple model formalizing the channels through which credit risk affects market liquidity. Our empirical analysis shows that credit risk affects market liquidity, and that this relation shifts conditional on the level of the CDS spread: it is stronger when the CDS spread exceeds 500 bp, a threshold used as an indicator by clearing houses in setting margins. Moreover, we show that the LTRO intervention by the ECB, which funneled funding liquidity into the banking system, weakened the sensitivity of market liquidity to credit risk.

We motivate our empirical analysis with a simple model of a risk averse market maker, holding an inventory of a risky asset and setting her optimal marginal quotes (and, therefore, the optimal bid-ask spread), in the presence of margin constraints and borrowing costs. The margins, set by a clearing house, depend on the risk of the asset, as measured by the CDS spread, and the actions of the central bank. The CDS market is fundamental to the market maker's and the clearing house's decisions, since it is from the CDS market that they deduce the future volatility of the asset return. In addition, the market maker can pledge her assets at the central bank to finance her positions at rates influenced by the central bank's actions. The model provides several empirical predictions that we test empirically.

First, we test the empirical prediction that the relation between the credit risk of a sovereign bond and its liquidity is statistically significant and, specifically, that the credit risk, as measured by the CDS spread, leads the liquidity, and not the other way around. Second, we examine whether the relation between credit risk and market liquidity is conditional on the level of the CDS spread, i.e., whether it is significantly altered when the CDS spread crosses a certain threshold. We find that the relation between market liquidity and credit risk is different, depending on whether the Italian CDS spread is below or above 500 bp. We interpret this finding, together with a change in the margins for bonds, in light of the predictions made by Brunnermeier and Pedersen (2009). Third, we analyze the impact of ECB intervention on the relation between credit risk and liquidity. We show that after the large amount of funding liquidity from the LTRO program has become available to market makers and market participants, changes in market liquidity respond to changes in credit risk with a significantly lower intensity.

To our knowledge, ours is the first paper to empirically investigate the dynamic relation between market liquidity and credit risk in the sovereign bond market, particularly during a period of crisis. The existing literature has highlighted the theoretical relation between bond yields and market liquidity, as well as that between funding liquidity and market liquidity (as modeled by Brunnermeier and Pedersen, 2009). We contribute to this literature by exploring the role of central bank interventions, and show both theoretically and empirically that they affect the relation between sovereign credit risk and market liquidity.

In the second essay, I extend the analysis of the determinants of market liquidity by considering the liquidity of an asset not by itself, but together with the liquidity of a second asset, which delivers exactly the same payoff of the first one, i.e., that is connected to the first one by an arbitrage relationship. I show that the market liquidities of the two assets co-move more when arbitrageurs are taking advantage of the mispricing between them. The co-movement of liquidity, also called commonality in liquidity, was simultaneously introduced by Chordia, Roll, and Subrahmanyam (2000), Hasbrouck and Seppi (2001), and Huberman and Halka (2001), and has since been shown to hold both within and across markets.

My first contribution, by detailing the trading strategies available to an arbitrageur, is to show in a simple trading framework how the market and limit orders submitted by arbitrageurs create co-movement across markets and lead to the convergence of bid prices, ask prices, and bid-ask spreads. Regardless of whether the arbitrageur employs limit or market orders in a specific quote setting, her trading strategies create a convergence, i.e., a positive correlation, between the bid prices in the two markets. By the same token, the arbitrageur's strategies imply a convergence between the ask prices and, ultimately, the midquotes and returns in the two markets. The co-movement between the pairs of quotes, bids and asks, results in the co-movement between the bid-ask spreads, that is, a co-movement between the liquidity measures in the two markets.

My second contribution is to empirically test this prediction that arbitrage activity increases the correlation between the liquidity in different markets. I do so by employing data on the quotes of 125 Canadian stocks that are cross-listed in the United States. During each of the six million trading seconds of 2013, for each of the 125 stocks, I establish whether an arbitrage opportunity was available between the stock listed in the United States and its counterpart traded in Canada, taking into account foreign exchange costs. I demonstrate the large degree of commonality in liquidity between securities linked by arbitrage between the Toronto and New York markets. I show that the co-movement between liquidity changes for securities connected by arbitrage is much larger during periods and for stocks with high arbitrage activity. For example, the correlation in liquidity changes over a one-minute interval is 7% for stock-days with a large number of arbitrage opportunities, and 25% for observations with a small number of arbitrage opportunities. Drawing from existing models and previous empirical work on commonality in liquidity, I identify other channels that would cause the liquidity of cross-listed stocks to co-move. In a multivariate regression setting, I regress the commonality in the liquidity measure on the metric of arbitrage activity and other proxies identifying alternative channels, to verify that the arbitrage channel does not weaken when other factors are taken into consideration. On the contrary, the effect of arbitrage trading on commonality in liquidity is still highly statistically significant and economically meaningful.

My third contribution is extending the previous finding outside the realm of stock markets alone. I consider a different arbitrage trade, the capital structure arbitrage, i.e., a trade that involves bonds and shares issued by the same company. I show that the commonality in liquidity between the bond and the stock market is higher when arbitrageurs are active, which supports the generality of my findings.

In the third essay we focus on characterizing how the market liquidity of a security spills over to a second security, connected to the first by arbitrage, specifically in the presence of a trader large enough to substantially affect the overall market liquidity. We term the phenomenon of the transmission of liquidity between assets linked by arbitrage as liquidity discovery, describing the process by which information is reflected in market liquidity, in a manner analogous to the concept of price discovery, which relates to the reflection of information in prices.

We use millisecond-level data from the cash and futures markets in the context of the Italian sovereign bond markets during the recent Euro-zone sovereign bond crisis and find that: (i) even though the futures market leads the cash market in price discovery, the cash market leads the futures market in liquidity discovery, i.e., the willingness of market makers to trade (measured by market depth and bid-ask spread), and (ii) the liquidity in the cash market, and not in the futures market, has a significant impact on the basis between the price of the futures contract and that of the bond.

In our investigation, we are mindful of the impact of ECB interventions on the linkage between these two markets in terms of price and liquidity. We shows that the introduction of the LTRO program, by providing liquidity to the banks, restored liquidity in both the futures and the cash bond market, drove the basis to zero and quickened the relationship between the illiquidity in the cash and future markets. The SMP intervention had the opposite result, widening the mispricing between the securities connected by arbitrage, removing liquidity from the bond market, thus finally affecting the liquidity of the futures market.

Essay 1

Sovereign Credit Risk, Liquidity, and ECB Intervention: *Deus ex Machina*?

with Loriana Pelizzon, Marti G. Subrahmanyam, and Jun Uno

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Abstract:
We examine the dynamic relation between credit risk and liquidity in the Italian sovereign bond market during the Euro-zone crisis and the subsequent European Central Bank (ECB) interventions. Credit risk drives the liquidity of the market: a 10% change in the credit default swap (CDS) spread leads to a 13% change in the bid-ask spread, the relation being stronger when the CDS spread exceeds 500 bp. The Long-Term Refinancing Operations (LTRO) of the ECB weakened the sensitivity of market makers' liquidity provision to credit risk, highlighting the importance of funding liquidity measures as determinants of market liquidity.

I Introduction

The challenges facing the governments of the GIIPS countries (Greece, Ireland, Italy, Portugal and Spain) in refinancing their debt marked the genesis of the Euro-zone sovereign debt crisis. Following a series of credit rating downgrades of three countries on the Euro-zone periphery, Greece, Ireland and Portugal, in the spring of 2010, the crisis spread throughout the Euro-zone. The instability in the Euro-zone sovereign bond market reached its apogee during the summer of 2011, when the credit ratings of two of the larger countries in the Euro-zone periphery, Italy and Spain, were also downgraded. This culminated in serious hurdles being faced by several Euro-zone countries, causing their bond yields to spike to unsustainable levels. The crisis has abated to some extent, due in part to fiscal measures undertaken by the European Union (EU) and the International Monetary Fund (IMF), but mostly thanks to the intervention by the European Central Bank (ECB) through a series of policy actions, including the Long-Term Refinancing Operations (LTRO) program, starting in December 2011.

The discussion in the academic and policy-making literatures on the Euro-zone crisis has mainly focused on market aggregates such as bond yields, relative spreads, and credit default swap (CDS) spreads and the reaction of the market to intervention by the Troika of the ECB, the EU and the IMF. Although the analysis of yields and spreads is useful, it is equally relevant for policy makers and market participants to understand the dynamics of market liquidity in the European sovereign debt markets, i.e., the drivers of market liquidity, particularly given the impact market liquidity has on bond yields, as documented in the previous literature on asset prices.

In this paper, we address the latter issue and analyze the inter-relation between market liquidity and credit risk, the effect of the funding liquidity of the market makers, and how this inter-relation changed thanks to the ECB interventions. We drive our analysis by developing a simple model that formalizes several channels through which credit risk affects market liquidity. Our empirical analysis shows that credit risk affects market liquidity, and that this relation shifts conditional on the level of the CDS spread: it is stronger when the CDS spread exceeds 500 bp, a threshold used as an indicator by clearing houses in setting margins. Moreover, we show that the LTRO intervention by the ECB, which funneled funding liquidity into the banking system, weakened the sensitivity of market liquidity to credit risk.

The linkage between credit risk and market liquidity is an important topic because a liquid market is of paramount importance for both the success of the implementation of central bank interventions, whether in the form of interest rate setting, liquidity provision funding, or quantitative easing, and their unwinding. Moreover, as we show in this paper, monetary policy has an impact on the interplay between credit risk and market liquidity itself.

The main focus of our research in this paper is to determine the dynamic relation between market liquidity and credit risk, as well as other risk factors such as global systemic risk, market volatility, and the funding liquidity risk of market makers. We study the effects of the ECB measures in the context of this dynamic relation. We employ the time-series of a range of liquidity metrics, as well as CDS spreads, a measure of credit quality, to analyze the liquidity of Italian sovereign bonds during the period from July 1, 2010 to December 31, 2012. We allow the data to help us uncover how the relation between credit risk and liquidity depends on the endogenous level of the CDS spread. In addition, we examine how these relationships were influenced by the interventions of the ECB.

We motivate our empirical analysis with a simple model of a risk averse market maker, holding an inventory of a risky asset and setting her optimal marginal quotes (and, therefore, the optimal bid-ask spread), in the presence of margin constraints and borrowing costs. The margins, set by a clearing house, depend on the risk of the asset, as measured by the CDS spread, and the actions of the central bank. The CDS market is fundamental to the market maker's and the clearing house's decisions, since it is from the CDS market that they deduce the future volatility of the asset return. In addition, the market maker can pledge her assets at the central bank to finance her positions at rates influenced by the central bank's actions. The model provides several empirical predictions that we test in the empirical section of the paper.

First, we test the empirical prediction that the relation between the credit risk of a sovereign bond and its liquidity is statistically significant and, specifically, that the credit risk, as measured by the CDS spread, leads the liquidity, and not the other way around. We find that a 10% change in credit risk is followed by a 13% change in market liquidity. Further, we find that the coefficients of both contemporaneous and lagged changes in the CDS spread are statistically and economically significant in explaining the market liquidity of sovereign bonds, even after controlling for the lagged liquidity variable and the contemporaneous changes in other factors. In particular, we test whether global risk and funding liquidity factors also affect market liquidity.

Second, we examine whether the relation between credit risk and market liquidity is conditional on the level of the CDS spread, i.e., whether it is significantly altered when the CDS spread crosses a certain threshold. We let the data identify the presence of such a CDS threshold effect, and find that the relation between market liquidity and credit risk is different, depending on whether the Italian CDS spread is below or above 500 bp. We find not only that a change in the CDS spread has a larger impact on market liquidity when the CDS spread is above 500 bp, but that this relation is instantaneous, while the lead-lag relation is stronger for lower levels of the CDS spread. We interpret this finding, together with a change in the margins for bonds, in light of the predictions made by Brunnermeier and Pedersen (2009).

Third, we analyze the impact of ECB intervention on the relation between credit risk and liquidity. The threshold effect in CDS levels is present only until December 21, 2011. In fact, our test for an endogenous structural break indicates that, on December 21, 2011 (when the ECB allotted the funds of the LTRO program), the relation between the two variables changes significantly. Thereafter, during 2012, after the large amount of funding liquidity from the LTRO program has become available to market makers and market participants, changes in market liquidity still respond to changes in credit risk, but with a lagged effect, and with a significantly lower intensity, while the only contemporaneous variable that affects market liquidity significantly is the global funding liquidity variable proxied by the Euro-US Dollar cross-currency basis swap spread (CCBSS).[1]

The Euro-zone sovereign crisis provides us with an unusual laboratory in which to study how the interaction between credit risk and illiquidity played out, in a more comprehensive framework than has been used in previous studies of corporate or other sovereign bond markets. In contrast to research on corporate bonds, which are generally traded over-the-counter (OTC), we have the advantage of investigating an exchange-traded market, using a unique, tick-by-tick data set obtained from the Mercato dei Titoli di Stato (MTS), the world's largest electronic trading platform for sovereign bonds. With respect to the US Treasury and other sovereign bond markets, the presence of a common currency for sovereign issuers means that the ECB is completely independent of the Italian government. Hence, the central bank's monetary policy has a qualitatively different impact on its sovereign credit risk, as well as on the market liquidity of its sovereign bonds, compared to countries whose central banks are somewhat within the control of the sovereign.

To our knowledge, ours is the first paper to empirically investigate the dynamic relation between market liquidity and credit risk in the sovereign bond market, particularly during a period of crisis. The existing literature has highlighted the theoretical relation between bond yields and market liquidity, as well as that between funding liquidity and market liquidity (as modeled by Brunnermeier and Pedersen, 2009). We contribute to this literature by exploring the role of central bank interventions, and show both theoretically and empirically that they affect the relation between sovereign credit risk and market liquidity. The laboratory for our analysis is the Italian sovereign bond market, particularly around the Euro-zone crisis, starting from July 2010. Italy has the largest sovereign bond market in the Euro-zone (and the third largest in the world after the US and Japan) in terms of amount outstanding, and is also a market that experienced substantial stress during the recent crisis. It is important to emphasize that such an analysis cannot be performed in

[1]This spread represents the additional premium paid per period for a cross-currency swap between Euribor and US Dollar Libor. Market participants view it as a measure of the macro-liquidity imbalances in currency flows between the Euro and the US Dollar, the global reserve currency.

other large sovereign bond markets, such as those of Germany or France, since they were not as much affected by the sovereign credit risk concerns.

In Section II of the paper, we survey the literature on sovereign bonds, particularly the papers relating to liquidity issues. In Section III, we present a model of market maker behavior in the setting of the bid-ask spread and derive its empirical implications. In Section IV, we provide a description of the MTS market architecture and the features of our database. In Section V, we present our descriptive statistics. Our analysis and results are presented in Section VI, and Section VII presents several robustness checks. Section VIII concludes.

II Literature Survey

The dynamic relation between credit risk and the market liquidity of sovereign bond markets has received limited attention in the literature, thus far. The extant literature on bond market liquidity seldom focuses on sovereign bond markets, with the exception of the US Treasury bond market; yet, even in this case, most papers cover periods before the current financial crisis and address limited issues related to the pricing of liquidity in the bond yields.[2] It is, therefore, fair to say that the relation between sovereign credit risk and market liquidity has not yet been investigated in the US Treasury market, possibly because US sovereign risk was not an issue until the recent credit downgrade by Standard & Poor's. The liquidity in the US Treasury bond market has been investigated by Chakravarty and Sarkar (1999), using data from the National Association of Insurance Commissioners, and Fleming (2003), using GovPX data. Fleming and Remolona (1999), Pasquariello and Vega (2007), and Goyenko, Subrahmanyam, and Ukhov (2011) study the responses of the US Treasury markets to unanticipated macro-economic news announcements. In a related paper, Pasquariello, Roush, and Vega (2011) study the impact of outright (i.e., permanent) open-market operations carried out by the Federal Reserve Bank of New York on the microstructure of the secondary US Treasury market. Furthermore, there are a few papers in the literature analyzing data from the electronic trading platform in the US known as BrokerTec, such as Fleming and Mizrach (2009) and Engle, Fleming, Ghysels, and Nguyen (2011).

There are a handful of papers on the European sovereign bond markets, and again, these papers generally examine a limited time period, mostly prior to the global financial crisis, and largely focus on the impact of market liquidity on bond yields; see for example Coluzzi, Ginebri, and Turco (2008), Dufour and Nguyen (2012), Beber, Brandt, and Kavajecz (2009), Favero, Pagano, and von Thadden (2010) and Bai, Julliard, and Yuan (2012). More recent work has highlighted the effects of ECB interventions on bond yields, market liquidity, and arbitrage relationships between

[2]Specifically, the existing literature documents the *direct* impact of liquidity (e.g., Dick-Nielsen, Feldhütter, and Lando, 2012, among others) on bond yields and prices, but not the impact of credit risk on liquidity, or how credit risk affects the bond yields through bond liquidity. In this spirit, we need to establish the relation between credit risk and liquidity in order to then, in turn, quantify its effect on bond yields. An effort in this direction is made by Jankowitsch, Nagler, and Subrahmanyam (2014).

fixed income securities. Ghysels, Idier, Manganelli, and Vergote (2014) study the effect of the Security Markets Programme (SMP) intervention on bond returns, while Corradin and Rodriguez-Moreno (2014) document the existence of unexploited arbitrage opportunities between European sovereign bonds denominated in Euros and Dollars, as a consequence of the SMP. Eser and Schwaab (2013) and Mesters, Schwaab, and Koopman (2014) show long- and short-term effects of the ECB interventions on European bond yields. Finally, Corradin and Maddaloni (2015) and Boissel, Derrien, Örs, and Thesmar (2014) investigate the relation between sovereign risk and repo market rates during the European sovereign crisis.

There is a vast literature on liquidity effects in the US corporate bond market, examining data from the Trade Reporting and Compliance Engine (TRACE) database maintained by the Financial Industry Regulatory Authority and using liquidity measures for different time periods, including the global financial crisis. This literature is relevant to our research both because it analyzes a variety of liquidity measures and because it deals with a relatively illiquid market with a vast array of securities. For example, Friewald, Jankowitsch, and Subrahmanyam (2012a) show that liquidity effects are more pronounced in periods of financial crisis, especially for bonds with high credit risk. Similar results have been obtained by Dick-Nielsen, Feldhütter, and Lando (2012), who investigate the effect of credit risk (credit ratings) on the market liquidity of corporate bonds.[3]

In a theoretical contribution to the literature on the relation between corporate credit risk and liquidity, Ericsson and Renault (2006) show both theoretically and empirically that bond illiquidity is positively correlated with the likelihood of default. He and Milbradt (2014) provide a theoretical framework for the analysis of corporate bonds traded in OTC markets and show that a thinner market liquidity, following a cash flow decline, feeds back into the shareholders' decision to default, making a company more likely to default. A final theoretical paper related to our analysis is by Brunnermeier and Pedersen (2009), who investigate the relation between funding liquidity and market liquidity.

To the best of our knowledge, there are no theoretical models that investigate the relation between *sovereign* credit risk and market liquidity. The models in Ericsson and Renault (2006) and He and Milbradt (2014) cannot be applied straightforwardly to the sovereign framework because of the nature of the credit event. There are, in fact, no bankruptcy or strategic default choices in the sovereign context (see Augustin, Subrahmanyam, Tang, and Wang, 2014, Section 7.1), although the outcome of debt renegotiation, e.g., the recovery rate, could arguably be affected by the liquidity of the secondary market. From a theoretical perspective, one channel that definitely applies to the relation between sovereign credit risk and market liquidity is that of the market maker's inventory concerns, as in the model proposed by Stoll (1978). In this paper we extend Stoll's (1978) model by

[3]Other recent papers quantifying liquidity in this market provide related evidence. See, for example, Edwards, Harris, and Piwowar (2007), Mahanti, Nashikkar, Subrahmanyam, Chacko, and Mallik (2008), Zhou and Ronen (2009), Jankowitsch, Nashikkar, and Subrahmanyam (2011), Bao, Pan, and Wang (2011), Nashikkar, Subrahmanyam, and Mahanti (2011), Lin, Wang, and Wu (2011), Feldhütter (2012), and Jankowitsch, Nagler, and Subrahmanyam (2014).

including further determinants of market liquidity, i.e., margins and a policy effect, whereby both margins and borrowing rates are influenced by the policy maker's actions (i.e., by the central bank). Our model is designed to specifically capture the effects that credit risk has on the market liquidity of bonds. A comprehensive theoretical model where sovereign credit risk, via debt renegotiations, affects market liquidity could be formulated; yet, such model lies beyond the scope of this paper. Nonetheless, in our empirical investigation, we allow and test for both the effects of credit risk on liquidity and liquidity on credit risk.

There are several important differences between the prior literature and the evidence we present in this paper. First, we are among the first to focus on the relation between liquidity (rather than yield spreads) in the cash bond market and credit risk, especially in the context of sovereign credit risk. Second, while most of the previous literature spans past, and thus more normal, time periods in the US and Euro-zone markets, the sample period we consider includes the most relevant period of the Euro-zone sovereign crisis. Third, our focus is on the *interaction* between credit risk and liquidity, i.e., how credit risk affects illiquidity and vice versa. Fourth, we examine the impact of monetary policy interventions on the linkage between credit risk and liquidity, in the context of ECB policies over the past few years, to measure and document their differential effects. Finally, we contribute to the literature a model that links the bid-ask spread in the bond market to the CDS market.

III The Model and its Testable Implications

In this section, we review and extend the standard model by Stoll (1978), in order to guide and motivate our empirical analysis. The extension allows us to define some simple concepts and gain an intuition about the forces driving the choice, by a market maker of a sovereign bond, of what bid-ask spread to quote on the market. The market maker stands ready to buy from, or sell to, an external trader, extracts information regarding the risk of the sovereign bond from the CDS market, and faces margin constraints arising from her inventory. The players in our model are i) the market maker, ii) other (external) traders buying or selling the bonds, iii) the clearing house, and iv) the central bank. The main purpose of our model is to characterize how a change in the CDS spread is reflected in the bid-ask spread of a bond issued by the underlying entity.[4] Figure 1 summarizes the players and the mechanisms of our model.

Insert Figure 1 here.

Central to the development of our model is identifying how the actions of each of the actors are affected by the credit risk of the bond that we are considering, and how, in turn, these actions affect the liquidity provided by the market maker. The model in Stoll (1978) shows that an increase in

[4]We thank the referee for suggesting we formalize our empirical predictions in a simple model.

the risk of the security is directly reflected in the market liquidity provision choice of the market maker (*Inventory Risk* in Figure 1). In addition to this direct channel, our model includes an *indirect* channel, through which the credit risk of the bond affects the liquidity provision choice of the market maker. The indirect channel relates to the dealer's cost of financing a bond in the repo market, including the margin requirements, when she has a non-positive inventory and she needs to sell a bond to a trader (*Margins* in Figure 1). In the indirect channel, credit risk affects the liquidity provision by the market maker through the clearing house's margin setting decision, which depends on the credit risk of the bond (*Margin Setting* in Figure 1). This hypothesis is motivated by the "Sovereign Risk Framework" adopted by LCH.Clearnet, the major European clearing house, and by other clearing houses, including Cassa di Compensazione e Garanzia, during the sovereign crisis: the framework states that the clearing house adjusts the margins based on a list of indicators, which includes the CDS spread and the bond yield spread over the German bund, to account for losses incurred in case of default by the issuer of the security (LCH.Clearnet, 2011).

The margin setting decision by the clearing house is also affected by the policies of the central bank, i.e., by i) the central bank's key interest rates, ii) the central bank's interventions, and iii) its explicit requests to the clearing house (*Funding Rate* and *Margin Framework* in Figure 1). First, the (collateralized) borrowing rate, set by the central bank, affects the volume traded on the repo market, by affecting its supply and demand, and, thus, the risk bearing capacity of the clearing house (see Mancini, Ranaldo, and Wrampelmeyer, 2014, for a detailed account of the effects of the ECB's interventions on the European Repo market).

Second, during the European debt crisis, the ECB enacted several extraordinary interventions: i) the Security Market Program (SMP), initiated in May 2010, ii) LTRO, announced and implemented in December 2011, iii) policy guidance, and iv) the outright monetary transactions (OMT), also announced in December 2011.[5] These interventions could affect the credit risk of the Eurozone, the liquidity of its bond market, or the funding liquidity of its banks: any of these effects should be taken into consideration by the clearing house, when setting margins. A similar implication can be drawn from the model by Brunnermeier and Pedersen (2009): the provision of funding liquidity relaxes the market makers' borrowing constraints and, consequently, the impact of margins on market liquidity.

Third, our hypothesis that central banks can affect even more directly the relation between margin settings and credit risk is supported by documents from the International Monetary Fund

[5]The SMP is a Eurosystem programme to purchase bonds—especially sovereign bonds—on the secondary markets. The last purchase under the SMP was made in February 2012. At its peak, in August 2011, the programme's volume totalled around âĆň210 billion. The LTRO interventions provided three-year funding of €489 billion on December 21, 2011 and €523 billion on February 29, 2012. The long-term maturity of this massive funding action was unprecedented in ECB policy history, and even globally. By policy guidance we largely refer to the Mario Draghi speech on July 26, 2012, at the Global Investment Conference in London, where he stated: "The ECB is ready to do whatever it takes to preserve the euro. And believe me, it will be enough." Outright monetary transactions is the programme to purchase sovereign bonds that substitute the SMP programme.

(2013) and the Bank of Italy (2012). Following a substantial margin increase by the clearing house LCH.Clearnet at a time of high credit risk, the Italian and French central banks worked with the clearing house to propose a shared methodology to ensure that margin requirements would depend smoothly on the CDS spread. This prevents the clearing house from implementing abrupt margin increases, disrupting the liquidity of the sovereign bond market when the sovereign credit risk is already high (Bank of Italy, 2012). The central banks requested the clearing house to avoid the possibility for margins to become procyclical to sovereign risk. Finally, in our model, the central bank affects the dealer's option to seek financing, by pledging the securities she holds, through changing the rate at which she can obtain funds (*Borrowing Costs* in Figure 1). One could also argue that the central bank's policy interventions themselves depend on the level of credit risk of the system (the dotted line in Figure 1). While we do not pursue this line of modelling, our predictions would be robust to the inclusion of this additional channel. Finally, our model aims at specifically capturing the effect of credit risk on bond market liquidity. While a model emphasizing the effect of a shock to market liquidity on credit risk in the sovereign context, possibly via debt renegotiation, could be developed, such a model lies beyond the scope of this paper.

We only model explicitly the behavior of the market maker, and assume as exogenous the other players' actions. In our model, we assume that the dealer, or market maker, is continuously making the market for a security; in this continuum in time, we choose an arbitrary point at which we model her optimal quote-setting decision. The dealer has an initial wealth of W_0 and an inventory made up of the bond with a dollar value equal to I. Moreover, she also invests a fraction k of W_0 in the market portfolio. She invests the remainder of her wealth, $(1-k)W_0 - I$ at the risk-free rate r_f, if $I < (1-k)W_0$, i.e., in case there is a surplus. However, if $I > (1-k)W_0 > 0$, she borrows the residual amount, by pledging securities in her portfolio at the central bank, at a rate $r_b = r_f + b$. Additionally, if the inventory position I is negative, she borrows the bond on the repo market, where it is subject to a margin requirement m. We model the margin, m, as an upfront cost of borrowing the specific bond rather than, for example, any bond under a general collateral agreement. In general, having to post margin constitutes a (opportunity) cost for the market maker, who would have otherwise allocated the required capital differently.

In light of our assumptions, we indicate the margin set by the clearing house as $m(b, CDS)$, i.e., a generic function of the CDS and the central bank liquidity policy, parametrized by the (collateralized) borrowing rate at the central bank. Following from the previous arguments, the margin setting decision depends on the credit risk and the policy arguments as follow: $\frac{\partial m(b,CDS)}{\partial CDS} > 0$, and $\frac{\partial m(b,CDS)}{\partial b} > 0$. We interpret the request of the central bank to avoid procyclical margin setting policies as a *shift* in the sensitivity of the margins to the level of the CDS spread, for a given level of borrowing rate, i.e., a shift in $\frac{\partial m(b,CDS)}{\partial CDS}|_b$.

If the dealer does not trade on the chosen date, the terminal wealth from her initial portfolio will be

$$W_I = W_0 k\,(1 + r_M) + I\,(1 + r) + \begin{cases} ((1-k)W_0 - I)\left(1 + r_f\right) & \text{if } (1-k)W_0 > I > 0 \\ ((1-k)W_0 - (1-m)\,I)\left(1 + r_f\right) & \text{if } (1-k)W_0 > 0 > I\,, \\ ((1-k)W_0 - I)\,(1 + r_b) & \text{if } I > (1-k)W_0 > 0 \end{cases}$$

where the market portfolio (expected) return is r_M ($\overline{r_M}$) and variance σ_m^2, and the bond (expected) net return is r ($\overline{r}$).[6] The (forward looking) variance of the bond return, which the market maker extracts from the CDS market, is $\sigma^2(CDS)$.

After trading a dollar quantity Q, the dealer's post-trading wealth is

$$\begin{aligned} W_{I+Q} =& W_0 k\,(1 + r_M) + (I+Q)\,(1+r) + C_Q(1+r_f) + \\ & \begin{cases} ((1-k)W_0 - (I+Q))\left(1 + r_f\right) & \text{if } (1-k)W_0 > I+Q > 0 \\ ((1-k)W_0 - (1-h)\,(I+Q))\left(1 + r_f\right) & \text{if } (1-k)W_0 > I+Q > 0 > I \\ ((1-k)W_0 - (I+Q))\,(1 + r_b) & \text{if } I+Q > (1-k)W_0 > 0 \end{cases} \end{aligned}$$

where C_Q is the dollar cost of entering into this transaction and depends on Q. These costs can be positive or negative, depending on whether the marginal trade in the bond raises or lowers the dealer's inventory-holding costs, and essentially captures the dealer's exposure cost of holding a non-optimal portfolio. The dealer has a constant absolute risk aversion utility function, $U(x) = -e^{-\gamma x}$, and she will trade and price the trade so that her expected utility from maintaining the existing portfolio is equal to the expected utility from trading the dollar quantity Q:

$$E\left[U\left(W_I\right)\right] = E\left[U\left(W_{I+Q}\right)\right].$$

In Appendix A, we show that the absolute bid-ask spread, calculated as the relative bid-ask spread for purchasing a quantity $Q = p_0$ multiplied by the price of the bond p_0, is

$$BA = \frac{\gamma p_0^2 \sigma^2(CDS)}{1 + r_f} + b\frac{p_0 - W_0\,(1-k)}{1 + r_f} + m(b, CDS)p_0. \tag{1}$$

The market maker observes the CDS price (CDS) on the CDS derivative market and extracts the (forward looking) volatility of the bond $\sigma(CDS)$. We model the relation between the standard deviation of returns and the CDS price by approximating it with a linear function, as in Brenner

[6] Since we aim to gain an understanding of the day-to-day change in a liquidity measure, we model the return of the bond as normally distributed between one period (day) and the next. This is a plausible assumption as long as the bond is neither near the maturity date nor in default, which is reasonable for our sample of Italian sovereign bonds.

and Subrahmanyan (1988), thus deriving $\sigma(CDS)$ as:

$$\sigma(CDS) = \left(1 + r_f\right) \frac{CDS}{p_0\, n\,(0)}, \tag{2}$$

where $n(0) \approx 0.4$ is the probability density function of the standard normal distribution evaluated at 0.[7]

Re-writing the absolute bid ask spread as a function of the CDS price, we obtain the relation between the dependent variable of interest, the absolute bid-ask spread, and its determinants, the CDS price, and the policy parameters set by clearing houses and the central bank:

$$BA(b, CDS) = \delta CDS^2 + m\,(b, CDS)\, p_0 + b\eta, \tag{3}$$

where $\frac{\gamma(1+r_f)}{n(0)^2} = \delta > 0$ and $\frac{p_0 - W_0(1-k)}{1+r_f} = \eta > 0$, and where we emphasize that the margin setting decision by the clearing house depends *both* on the borrowing cost set by the central bank and on the level of the CDS.[8]

Equation (3) features the two channels through which the first determinant of market liquidity, the CDS price, affects the bid-ask spread. The first channel, represented by the first term in the equation (δCDS^2), is a direct one, arising from the market maker's update of the (forward looking) bond volatility, as extracted from the derivative market. The second channel, the second term in the equation ($m\,(b, CDS)\, p_0$), is an indirect effect of the CDS price through the margin setting decision by the clearing houses, since the clearing houses, like the market maker, extract information about the riskiness of the bond from the CDS market. Our model rationalizes how changes in margins, which depend on the level of the CDS spread (or price), affect the relation between credit risk and liquidity.

A second determinant of market liquidity is the central bank's monetary policy, which affects both the market maker's borrowing costs, through the third term in the equation ($b\eta$), and the second (indirect) channel through which the CDS price affects the liquidity: the margin settings. The monetary policy affects the margin setting decision by the clearing house, which influences the market maker's decision via the second term in the equation ($m\,(b, CDS)\, p_0$). In the next subsection, we derive the empirical predictions of the model that we test in the data.

III.A Empirical Predictions

Empirical Prediction 1 *The illiquidity of the bond market increases with credit risk.*

[7]This is a partial equilibrium analysis; in a general equilibrium model, a change in volatility via *CDS* would also change p_0, as the underlying asset price would in a general version of the Black-Scholes model. In our model, therefore, we assume that the asset price is exogenous, and focus on changes in the return volatility. All detailed calculations deriving the model can be found in Appendix A.

[8]The second inequality follows from the requirement that the market maker borrows the residual amount, when buying a bond, by pledging the security at the central bank, as modeled in Appendix A.

This follows from Equation (3), as $\frac{\partial BA}{\partial CDS} > 0$, since $\delta > 0$, $\eta > 0$, and $\frac{\partial m(b,CDS)}{\partial CDS} > 0$. We expect an increase in credit risk to raise the market illiquidity of the bond. As in the Stoll (1978) model, and in line with other inventory models of market microstructure, our model predicts that an increase in the risk of a security, e.g., credit risk, implies a riskier inventory, leading to a withdrawal of liquidity offered to the market by the market maker.

Since we expect the change in credit risk to be a relevant variable in characterizing the *dynamics* of liquidity in the market through the market makers' inventory concerns, we investigate the lead-lag relation between credit risk and illiquidity, and the directionality of this relation.[9]

Moreover, our first empirical prediction is in line with risk management practices based on value-at-risk (VaR) models used widely by market participants, particularly the market makers. A portfolio with an excessively large VaR, due to credit risk, erodes the dealers' buffer risk capacity, which results in the dealer setting higher bid-ask spreads.[10]

Empirical Prediction 2 *The dynamic relation between credit risk and market illiquidity shifts conditional on the level of the CDS spread.*

We derive from Equation (3) the sensitivity of the bid-ask spread to the CDS spread, $\frac{\partial BA}{\partial CDS} = 2\delta CDS + \frac{\partial m(b,CDS)}{\partial CDS}$. This sensitivity depends on the CDS spread through two channels: the direct risk channel, and the indirect margin setting channel; Empirical Prediction 2 focuses on the latter. As documented in LCH.Clearnet (2011), the "Sovereign Risk Framework" states that the margin-setting decisions depend on the level of CDS and, particularly, that the clearing house deems that the risk of a security has increased significantly if the 5-year CDS spread increases above 500bp. In our model, this dependence would translate into a shift in $\frac{\partial m(b,CDS)}{\partial CDS}$, when the CDS spread crosses the 500bp threshold.[11]

To test this empirical prediction, we employ the threshold test proposed by Hansen (2000) to investigate i) whether a structural break in the level of CDS is present in the relation between credit risk and liquidity, ii) if this threshold corresponds to 500 bp, and iii) how the relation between credit risk and market liquidity changes, below and above the threshold.[12]

Empirical Prediction 3 *The monetary policy interventions of the central bank affect the dynamic relation between credit risk and market liquidity.*

[9]We address the contemporaneous interaction between the two variables in detail in Section Int.1 of the internet appendix, via instrumental variables analysis.

[10]This link also has implications for the *dynamics* of the relation between credit risk and market liquidity: The VaR is calculated at the end of day $t-1$. In periods of market stress, however, the VaR is often monitored at an intraday frequency, implying that day-t liquidity will depend on the contemporaneous, day-t, credit risk.

[11]Other related conceptual arguments can be advanced for such a shift in the relation. First, during the Euro-zone crisis, the adverse change in credit quality was generally accompanied or followed by downgrades in the credit rating, altering the clientele of investors who were able to hold Italian sovereign bonds. Second, in the presence of a sharp decline in credit quality, internal (and external) models of risk-weighting and illiquidity used by banks, a major investor segment, would necessarily predict an increase in the capital required to support the higher level of risk.

[12]Appendix B presents the details of the econometrical procedure.

A central bank intervention that targets the access to funding liquidity by banks and market makers would, in our model, affect the sensitivity of the bid-ask spread to the CDS spread by changing the clearing houses margin setting decision, i.e., through $\frac{\partial m(b,CDS)}{\partial CDS}$. In the context of the relation between credit risk and liquidity, therefore, a successful intervention would be one that affects the sensitivity of the market makers to changes in credit risk by providing them with improved funding liquidity. Therefore, we especially expect the LTRO to have an impact, due to the nature of its large funding liquidity shock, qualifying it as a significant structural break, thus affecting the market liquidity in the sovereign bond market through the availability of funding liquidity to market makers. As in Brunnermeier and Pedersen (2009), we expect the margin channel to be have a larger impact on the market maker's liquidity provision when she is funding-liquidity constrained. The availability of massive amounts of medium-term funding from the ECB, at unusually low interest rates, should have shifted the incentives of dealers to hold sovereign bonds.

Our third empirical prediction investigates the presence of regime shifts in the estimated relation between credit risk and market liquidity around the dates of significant policy interventions by the ECB. Due to the large number of such interventions (SMP, LTRO, OMT, policy guidance, as described above) during the Euro-zone crisis, we choose to allow the data to endogenously inform us of the presence of structural breaks that indicates whether these interventions indeed affected the relation between credit risk and market liquidity. To investigate this issue, we perform a SupWald structural break test, a modified Chow test with an unknown break point (see Chow, 1960; Andrews, 1993; Hansen, 1997). Appendix B presents the procedure in detail.

As argued earlier, the ECB interventions and its moral suasion towards the clearing houses could affect the sensitivity of the market liquidity to the credit risk via the indirect margin channel and, thus, affect the findings established in the previous empirical predictions. Therefore, we replicate the analysis in Empirical Prediction 1 and 2, for the two periods identified by the statistical procedure. Thus, for the two periods separately, we i) quantify the sensitivity of the bid ask spread to the CDS spread, and ii) test whether the relation shifts, when the CDS spread is above a threshold.

IV MTS Market Structure and Description of Variables

Our data consist of all real-time quotes, orders, and transactions that took place on the MTS European sovereign bond market during our period of study, and are provided by the MTS Group. These high-frequency data cover trades and quotes for the fixed income securities issued by twelve national treasuries and their local equivalents: Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal, Slovenia, and Spain. The MTS system is the largest interdealer market for Euro-denominated sovereign bonds and is made up of many markets, including the EuroMTS (the "European market"), EuroCredit MTS, and several domestic MTS markets. In this study, we will focus on the liquidity of Italian sovereign bonds, regardless of whether the trading or quoting activity took place on the domestic or the European market. The MTS trading system is an automated quote-driven electronic limit order interdealer market, in which market makers' quotes can be "hit" or "lifted" by other market participants via market orders. EuroMTS is the reference electronic market for European benchmark bonds.[13]

The sample period of our study is from July 1, 2010 to December 31, 2012.[14] The time period we analyze provides a good window in which to study the behavior of European sovereign bond markets during the most recent part of the Euro-zone sovereign debt crisis and the period leading up to it. Our data set consists of 189 Italian sovereign bonds. Table I presents the distribution of these bonds in terms of maturity and coupon rate, among original maturity groups as well as bond types. In terms of maturity groups, the bonds are grouped together based on the integer closest to their original maturity. As Table I shows, the large majority (in numbers) of the bonds analyzed have short maturities (from 0 to 5 years). All bonds considered in this analysis belong to one of the following types: Buoni Ordinari del Tesoro (BOT), which correspond to Treasury bills, Certificato del Tesoro Zero-coupon (CTZ), corresponding to zero-coupon bonds, Certificati di Credito del Tesoro (CCT), or floating notes, and Buoni del Tesoro Poliennali (BTP), which are coupon-bearing Treasury bonds. The vast majority of the bonds in our sample belong to the BOT and BTP types. We exclude inflation and index-linked securities from our analysis.

Insert Table I here.

IV.A Description of Variables

We measure bond liquidity for the MTS market by the daily *Bid-Ask Spread*, defined as the difference between the best ask and the best bid, per €100 of face value, proxying for the cost of immediacy that a trader will face when dealing with a small trade. We measure the bid-ask spread per bond at a five-minute frequency from the market open to the market close, namely from 8 AM to 5.30 PM, then average it per bond throughout the day, and finally average the daily bond measures across bonds to obtain a market-wide daily liquidity measure.

The Italian-sovereign-specific credit risk is measured by the spread of a senior five-year dollar-denominated CDS contract obtained from Bloomberg. The choice of this proxy for sovereign credit risk is debatable. An alternative potential proxy for Italian sovereign risk could be the BTP-Bund

[13]Benchmark bonds are bonds with an outstanding value higher than €5 billion. Section Int.2 of the internet appendix provides details of the market architecture, trading protocol, and data released for the MTS market; see also Dufour and Skinner (2004).

[14]Our data set from July 2010 to May 2011 includes only intraday updates of the three best bid and ask quotes. From June 1, 2011, we have detailed tick-by-tick, second-by-second, data. The end date is dictated by a major change in market structure that was implemented in December 2012, and that changed the role of market makers acting in the European section of the MTS market. Fortuitously, the period we consider covers a large part of the Euro-zone crisis. A more detailed description of the differences between the datasets can be found in the internet appendix, Section Int.2.

yield spread. We prefer to avoid using the BTP-Bund yield spread because this variable is likely to be intimately connected to the bond quote and transaction prices that are also used to calculate our liquidity measures. CDS spreads are obviously related to the BTP-Bund yield spread (as Figure 2 shows), through arbitrage in the basis between them, but at least are determined in a different market.[15]

Insert Figure 2 here.

Finally, in order to control for and characterize the effect of global credit risk and funding liquidity, we employ several macro-economic indicators, most of which are common in the academic literature. The Euribor-DeTBill yield spread captures the (global) counterparty and credit risk and, thus, an increase in the cost of funding, and is measured as the difference between the three-month Euro-area Inter-Bank Offered Rate (Euribor) for the Euro, covering dealings from 57 prime banks, and the three-month yield of the three-month German Treasury bill. As banks are more uncertain, they charge each other higher rates on unsecured loans; similarly, looking for high-quality collateral, they purchase safe Treasury bills, lowering their yields. This measure is the European counterpart of the TED spread used by, among others, Brunnermeier (2009). The USVIX, measuring global systemic risk, is the implied volatility index of S&P 500 index options calculated by the Chicago Board Options Exchange (CBOE) and used widely as a market sentiment indicator. The CCBSS represents the additional premium paid per period for a cross-currency swap between Euribor and US Dollar Libor, and serves as a proxy for funding liquidity.[16] All these variables were obtained from Bloomberg.

V Descriptive Statistics

Table II presents the summary statistics for the market activity measures for Italian sovereign bonds traded on the MTS market and system variables, between July 2010 and December 2012, spanning the period of the Euro-zone sovereign crisis. The table reports statistics for the daily time-series of the market-wide variables: *Trades*, *Volume*, and *Bid-Ask Spread* were calculated on a daily bond

[15]We show in Section Int.3 of the internet appendix that there is no statistically significant lead-lag relation between the two daily series, because the adjustment between them takes place on the same day. Also, in Section Int.4 of the internet appendix, we investigate whether the intraday volatility of the bond yield, as measured using the MTS transaction data, and the liquidity of the CDS market affect the liquidity, while controlling for the credit risk. These modifications do not significantly change the results, supporting our choice of the CDS spread as a measure of credit risk.

[16]The CCBSS can be thought of as the spread of the longer-term, multi-period equivalent of deviations from uncovered interest rate parity. When liquidity is available to arbitrageurs in all currencies, deviations from the (un)covered interest rate parity will be closed and profited on, while lasting deviations can be interpreted as a sign of lack of funding liquidity. Baba, Packer, and Nagano (2008) and Baba (2009) show that cross-currency basis swaps are used by banks to finance themselves in foreign currencies when the interbank market in the home currency is illiquid, Brunnermeier, Nagel, and Pedersen (2008) show that deviations from uncovered interest rate parity are partially explained by shocks to funding liquidity. Acharya and Steffen (2015) and Ivashina, Scharfstein, and Stein (2012) investigate the funding liquidity needs of European banks and relate them to the (un)covered interest rate parity.

basis and then averaged across bonds to obtain the time-series. *Quoted Bonds* is the time-series of the number of bonds quoted each day.

Insert Table II here.

The mean (median) number of bonds quoted each day on the MTS is 89 (88), and the daily volume of trading in the market is slightly below €2.9 billion (€2.6 billion), which translates into a daily traded volume for each quoted bond of about €32.6 million (€28.7 million). Based on these numbers, the daily trading volume in the Italian sovereign bond market (as represented by the MTS) is much smaller than in the US Treasury market, by a couple of orders of magnitude, with the average traded quantity in the latter being around $500 billion per day (Bessembinder and Maxwell, 2008). The average daily trading volume in the MTS Italian bond market is even smaller than in the US municipal market (around $15 billion), the US corporate bond market (around $15 billion), and the spot US securitized fixed income market (around $2.7 billion in asset-backed securities, around $9.1 billion in collateralized mortgage obligations, and around $13.4 billion in mortgage-backed securities).[17]

Our volume statistics are in line with the stylized facts documented in the previous literature, taken together with the consistent shrinkage of overall market volumes since the Euro-zone crisis began. Darbha and Dufour (2013) report that the volume of the Italian segment of the MTS market as a whole, over their 1,641-day sample, was €4,474 billion. This translates into an average daily volume of about €3.8 billion. Darbha and Dufour report that the daily volume per bond shrank from €12 million in 2004 to €7 million in 2007. Their sample includes only coupon-bearing bonds; thus, their figures for overall market volume are not directly comparable to ours.

The daily number of trades on the MTS Italian sovereign bond market is 352 in total (or about 4 per bond), which is similar to the 3.47 trades a day per corporate bond on TRACE, as reported in Friewald, Jankowitsch, and Subrahmanyam (2012a). Dufour and Nguyen (2012) report an average of 10 trades per day per Italian bond in an earlier period, between 2003 and 2007. As with the trading volume, the number of trades declined during the crisis period compared to earlier years. Our sample period covers the most stressed months of the Euro-zone crisis, when the creditworthiness of several European countries was seriously questioned by market participants. As we will show later, the liquidity in the MTS market was intimately related to the evolution of spreads in the sovereign CDS market, and varied just as drastically, as the time-series plots of the CDS spread and the *Bid-Ask Spread* in Figure 2 show. Up to the end of 2011, at the peak of the crisis, the two series share a common trend, which is not repeated in the second half of our sample.

The commonality in the two series in Figure 2 becomes particularly evident, for example, when one considers the highest spike for the *Bid-Ask Spread* (€4.48 per €100 of face value), which

[17] Details for the corporate bond, municipal bond, and securitized fixed income markets are provided in Friewald, Jankowitsch, and Subrahmanyam (2012a), Vickery and Wright (2010), and Friewald, Jankowitsch, and Subrahmanyam (2012b), respectively.

happened on November 9, 2011. On the previous day, after the markets had closed, the Italian Prime Minister, Silvio Berlusconi, lost his majority in the parliament, which led to his resignation. The spike in the *Bid-Ask Spread* corresponds to a similar spike in the *CDS Spread*. The event clearly had medium-term effects, as both the *Bid-Ask Spread* and the *CDS Spread* persisted at high levels for about two months, before returning to more moderate quantities in January 2012. In mid-2012, however, the *CDS Spread* reached levels close to 500 bp, while the *Bid-Ask Spread* oscillated around the time-series median value of €0.30.

The reasons for choosing to present our results based on the bid-ask spread as a measure of market liquidity bear mention. First, the quoted bid-ask spread is the most familiar and widespread measure of market liquidity. Thus, it allows for a direct comparison with the previous and contemporaneous literature on liquidity. Second, the large number of quotes that are aggregated into a single daily bid-ask spread time-series suggests that market makers are very active, and ensures that the computed spread is a precise estimate of their willingness to trade, since the quotes are firm. Finally, high-frequency quote updates indicate that accurate quoting in the MTS market is important for primary dealers under the supervision of the Bank of Italy. These quotes are, moreover, also used by officials at the Italian Treasury to evaluate (and eventually even disqualify) sovereign bond market makers.[18]

The results of the Dickey-Fuller unit root test for the variables used in our empirical investigation are presented in Table II under the "Unit Root Test" columns for the levels of and differences in the variables. All our tests for the control variables and the CDS spread support the existence of a unit root, while the bid-ask spread and the USVIX show a mean-reverting property. However, (i) the first-order auto-correlation for the liquidity measure is 81%, and (ii) the unit root test did not reject the unit root null hypothesis when it was performed on the first part of the sample, for the period when the Euro-zone crisis first unfolded. In light of this fact, and in order to have a consistent, unique model for the whole data sample and to ensure well-behaved residuals, we perform our analysis in first differences.

As shown in Figure 2, the Italian CDS spread for our sample period ranges from 127 bp to 592 bp, with a mean of 321 bp and a standard deviation of 138 bp, indicating the large changes in this variable during the period under study. Figure 3 shows the evolution of the macro variables. The Euribor-DeTBill spread (Panel (a)) also presents a significant level of volatility, with a daily standard deviation of 0.36%, while the USVIX (Panel (b)) ranges from 13.45% to 48%. The CCBSS variable (Panel (c)), which captures the general level of funding liquidity in the system, and which should be close to zero in the absence of funding constraints, ranges from 12bp to 107bp, indicating a large variability in the global liquidity conditions in the Euro-zone in the

[18]From July 1, 2010 until May 31, 2011, we use the MTS database that provides only the three best bid and ask prices. However, we have an overlapping sample of seven months of both the databases, and perform a comparison of the bid-ask liquidity measure we calculate, using the two databases. The results show that there is almost no difference between the two, for the purpose of computing the bid-ask spread; see Section Int.2 of the internet appendix.

period considered. All the funding and credit variables suggest that the conditions in the Euro-zone financial system were at their worst around the third quarter of 2011, but improved somewhat during the first quarter of 2012, then worsened, although to a lesser extent, around June 2012, and continued to decline towards the end of that year.

Insert Figure 3 here.

The correlations between the credit, funding liquidity and market liquidity variables are shown in Table II Panel C. The correlations between the variables in levels are presented above the diagonal, while those for the variables in differences are below the diagonal. In differences, bond market liquidity is most highly correlated with the Italian *CDS Spread* and the CCBSS.

VI Results

In Section III we derived three empirical predictions and, in this section, we investigate them, focusing on the dynamic relationships between credit risk and market liquidity and the effect of the ECB's *deus ex machina*. In order to test the first empirical prediction, regarding the dynamics of the relation between the credit risk of Italian sovereign bonds, as measured by the *CDS Spread*, and the liquidity of the Italian sovereign bonds, as measured by their *Bid-Ask Spread*, we first investigate, in Section VI.A, whether there is a lead-lag relation between the two variables, using a Granger-causality test in a Vector Auto Regression (VAR) setting.[19]

In Section VI.B, we focus on Empirical Prediction 2, and test for the presence of a threshold in the level of the CDS spread that shifts the relation between credit risk and market liquidity. We perform this analysis using the threshold test proposed by Hansen (2000), and characterize how the relation between credit risk and market liquidity changes below and above this threshold. Finally, in Section VI.C, we investigate Empirical Prediction 3 and test whether and how the dynamics of the relation are affected by the ECB interventions. We use an endogenous structural break test described in detail in Appendix B, and study whether the injection of funding liquidity by the central bank lowered the sensitivity of market liquidity to the worsening credit conditions of the Italian sovereign.

VI.A The Dynamics of Credit Risk and Liquidity

Empirical Prediction 1 *The illiquidity of the bond market increases with credit risk.*

[19]We conduct our analysis in changes, after winsorizing the data at the 1% level to diminish the importance of outliers, such as the large changes in bid-ask spread in the second half of 2011, in particular that of November 9. For robustness, we repeat the analysis after winsorizing the data at the 5% level. The results are mostly unchanged and reported in the internet appendix Section Int.5.

In this section, we investigate Empirical Prediction 1, testing whether the increase in credit risk drives the reduction of market liquidity or vice versa. While our theoretical model has been explicitly designed to characterize the effects that a change in the credit risk has on the market liquidity, we cannot rule out that market liquidity has, in turn, an effect on credit risk. Therefore, to allow for this feedback loop, we implement this analysis by estimating a VAR system that allows us to perform a Granger-causality test. Since global risk factors could affect market liquidity, on top of security-specific credit risk concerns, we include USVIX, the Euribor-DeTBill spread, and the CCBSS in our VAR specification as "exogenous variables". These variables are exogenous in that we are not interested in studying the effect of the endogenous variables on their dynamics, only the opposite effect. We thus describe the system using a VAR with eXogenous variables (VARX) model.

The mathematical formulation of this Granger-causality test is based on linear regressions of the change in the *Bid-Ask Spread*, ΔBA_t, and the change in the *CDS Spread*, ΔCDS_t, on their p lags. Specifically, let ΔBA_t and ΔCDS_t be two stationary daily time-series, and X_t a time-series $m-$vector of stationary exogenous variables. We can represent their linear inter-relationships using the following VARX model:

$$\begin{pmatrix} \Delta BA_t \\ \Delta CDS_t \end{pmatrix} = \begin{pmatrix} K_{BA} \\ K_{CDS} \end{pmatrix} + \sum_{i=1}^{p} \begin{pmatrix} a_{11_i} & a_{12_i} \\ a_{21_i} & a_{22_i} \end{pmatrix} \begin{pmatrix} \Delta BA_{t-i} \\ \Delta CDS_{t-i} \end{pmatrix} + \sum_{j=0}^{q} B_j \begin{pmatrix} \Delta X1_{t-q} \\ \Delta X2_{t-q} \\ \vdots \\ \Delta Xm_{t-q} \end{pmatrix} + \begin{pmatrix} \epsilon_{BAt} \\ \epsilon_{CDSt} \end{pmatrix}, \tag{4}$$

where $\epsilon_{\mathbf{t}} \sim N(\mathbf{0}, \mathbf{\Omega})$, the B_js are 2-by-m matrices, and the a_{ij_p}s are the p-lag coefficients of the model. This formulation allows for the presence of m contemporaneous, and lagged (up to q), exogenous variables to control for factors that might affect the dynamics of the endogenous variables. We can conclude that ΔCDS Granger-causes ΔBA when the a_{12_p}s are contemporaneously different from zero. Similarly, we can surmise that ΔBA Granger-causes ΔCDS when the a_{21_p}s are contemporaneously different from zero. When both these statements are true, there is a feedback relation between the two time-series.

The lag length was chosen based on the corrected Akaike criterion, which suggests a lag length of 3 for the endogenous variables and no lagged exogenous variables. The results of the Granger-causality test, with $p = 3$ and $q = 0$, for the relation between the changes in the *CDS Spread* and the *Bid-Ask Spread*, are reported in Table III, where we report the F-test test statistics for the contemporaneous significance of the cross-variable terms for each equation (the a_{12}s for the bid-ask spread equation under ΔBA_t, and the a_{21}s for the CDS spread equation under ΔCDS_t).[20]

Insert Table III here.

[20]Throughout the paper, statistical significance is always determined on the basis of t-tests that are calculated using heteroskedasticity-robust standard errors.

As the table shows, in line with Empirical Prediction 1 in Section III, the *CDS Spread* Granger-causes liquidity in the bond market at a 1% level (the heteroskedasticity-robust F-test is 6.01 and the 1% confidence value is 3.81, and the bootstrapped results provide identical significance levels), while the opposite directionality is not significant at any of the usual confidence levels (the p-value is 0.70). This result confirms Empirical Prediction 1 and supports the inventory risk channel as a driver of the relation between credit risk and market liquidity.

The macro variables are significant in explaining the two variables. Specifically, the bond market illiquidity depends positively on the availability of funding liquidity for European banks and on the sentiment of the market, as measured by the $CCBSS$ and $USVIX$, respectively. In untabulated results, however, the contemporaneous dependence of the macro variables does not lower the significance of the effect of (lagged) credit risk on market liquidity, although it contributes towards lowering the residual cross-correlation.

In order to interpret the dynamics of the system, we calculate the impulse response functions (IRF) for the relationships between the variables. We do this for the rescaled variables, so that they have a mean of 0 and a standard deviation of 1, for ease of interpretation. Figure 4 presents the results, for which the 5% confidence bands were bootstrapped based on 5,000 repetitions. As shown in Panel (a) of the figure, a one-standard-deviation shock to the *CDS Spread* at time 0, corresponding to a 4.1% change, is followed by a change of 0.26 standard deviations in the *Bid-Ask Spread*, corresponding to a 5.2% increase in the same direction, and is absorbed by both variables in two days. Alternatively, the parameters imply that a 10% change in the *CDS Spread* (corresponding to a change of $10\%/4.1\% = 2.43$ standard deviations) is followed by a $2.43 \cdot 5.2 = 12.7\%$ change in the *Bid-Ask Spread*. The results are, hence, both statistically and economically significant, and confirm the results of the Granger-causality tests presented above. The IRF in Panel (b) shows that a shock at time 0 to market liquidity lasts until time 1, but only affects market liquidity itself, indicating that the reaction of the *CDS Spread* to a shock in market liquidity is never different from zero, in line with the findings of the Granger-causality tests.

Insert Figure 4 here.

Since the focus of this study is the dynamics of the credit risk and bond market liquidity in relation to each other, and past values of bid-ask spread do not affect credit risk, as per Table III, we focus solely on the bid-ask spread regression in the VARX system, augmenting it with the contemporaneous change in credit risk. This corresponds to a shift from a reduced-form to a structural approach for the VAR, where the contemporaneous causation runs from credit to liquidity. As the ordering of the variables in this causation chain cannot be tested in the VAR setting (see, e.g., Lütkepohl, 1993), we turn to instrumental variable (IV) methods to establish whether feedback between the contemporaneous *CDS Spread* and *Bid-Ask Spread* changes—or, alternatively, other forms of endogeneity—is supported by the data. We do so to ensure that our specification does not disqualify the structural approach we take, or otherwise suggest the opposite relation. In Section Int.1 of the internet appendix, we show using several cohorts of valid and strong instruments that the *CDS Spread* is indeed not endogenous to the system, and hence its inclusion as a regressor is justified: the regression parameter attached to it in the bid-ask spread regression is unbiased and consistently estimated.

As both the lead-lag and the contemporaneous relation indicate the direction of the Granger-causality, we only need focus in the rest of the paper on the causal effects on the liquidity measure (i.e., the ΔBA_t equation), in order to determine the dynamics of the system. This will be sufficient to capture the dynamics of the credit-liquidity relation (including the effect of ECB interventions), given the lack of statistical support for causality in the opposite direction. Therefore, we regress changes in the liquidity measure, *Bid-Ask Spread*, on the contemporaneous changes in the *CDS Spread*, and their respective lags, and on the contemporaneous macro variables. Equation (5) presents our baseline regression specification for the remainder of the paper:

$$\Delta BA_t = \alpha_0 + \sum_{i=1}^{3} \alpha_i \Delta BA_{t-i} + \sum_{j=0}^{1} \beta_j \Delta CDS_{t-j} + \beta_2 CCBSS + \beta_3 USVIX_t + \epsilon_t, \tag{5}$$

where ΔBA_t is the change in the bond-market-wide bid-ask spread from day $t-1$ to day t, and ΔCDS_t is the change in the CDS spread, as before. The statistically insignificant lags of the CDS measure and $\Delta EuriborDeTBill_t$ have been dropped due to their lack of statistical significance. The results for Equation (5) are reported in Table IV Panel A.

Comparing the parameters in Table IV Panel A to those in Table III shows that adding the contemporaneous change in the *CDS Spread* does not modify our findings, with the exception of a lower level of statistical significance for the other contemporaneous variables. This was to be expected, since these other variables potentially proxy for changes in the credit risk. Moreover, the dynamics of the bid-ask spread are well accounted for, since the residuals show no autocorrelation according to the Durbin h-test and the Breusch-Godfrey serial correlation test (never significant at the 10% level or lower for lags up to 10, with one exception).

Insert Table IV here.

As for the dynamics of the system, the change in the *CDS Spread* has a lagged effect on market liquidity, i.e., the reaction of market liquidity, measured by the *Bid-Ask Spread*, to changes in the *CDS Spread*, occurs on the next day. The *Bid-Ask Spread* also shows evidence of an autoregressive component, being strongly related to the change in the *Bid-Ask Spread* that took place the day before, with a negative sign: this suggests an overreaction adjustment dynamic in the *Bid-Ask Spread*, as shown already in the IRF of Figure 4 Panel (b). This effect can be ascribed to the actions of the market makers, who adjust their quotes as a reaction, not only to the changes in the traded price, but also to the changes in the quotes of the other primary dealers. A 10% increase in the CDS spread on day t results in an increase in the bid-ask spread of 5.41% on day t and a further increase of $-0.352 \cdot 5.41\% + 7.94\% = 6.04\%$ on day $t+1$, for a cumulative increase of 11.45%.

Regarding the significance of the lagged ΔCDS term, a partial explanation can be found in the timing of VaR-based models in practice. Since the calculation of the dealer's VaR generally takes place at the end of the day, the exposure to the credit risk is taken into account by the dealer when deciding how much liquidity to offer only on the day following the credit shock, which implies the significance of the lagged change in credit risk.[21]

VI.B The relation between Credit Risk and Liquidity Conditional on the Level of Credit Risk

Empirical Prediction 2 *The dynamic relation between credit risk and market illiquidity shifts conditional on the level of the CDS spread.*

Turning to our Empirical Prediction 2, Equation (5) above implicitly assumes that the estimated relation holds independent of the *level* of credit risk, in particular when the *CDS Spread* is above a particular threshold level. For the reasons highlighted in the theoretical model presented in Section III, on account of margin setting, and downgrade concerns, it is possible that the market makers' liquidity provision would be more sensitive to changes in credit risk when the *CDS Spread* breaches a particular threshold. We investigate this empirical prediction by allowing the data to uncover the presence of a threshold in the level of the *CDS Spread*, above which a *different* relation between changes in CDS and changes in market liquidity is observed. We use the test proposed by Hansen (2000), described in detail in Appendix B, to examine this hypothesis, estimating Equation (6) for different γ, where $I\left[CDS \leq \gamma\right]$ equals 1 if the condition is satisfied and 0 otherwise:

$$\Delta BA_t = \alpha_0 + \sum_{i=1}^{3} \alpha_i \Delta BA_{t-i} + I\left[CDS \leq \hat{\gamma}\right]\left(\sum_{j=0}^{1} \beta_j \Delta CDS_{t-j}\right) + I\left[CDS > \hat{\gamma}\right]\left(\sum_{j=0}^{1} \tilde{\beta}_j \Delta CDS_{t-j}\right) + \beta_2 USVIX_t + \beta_3 CCBSS + \epsilon_t. \tag{6}$$

Figure 5 shows, on the y-axis, the sum of squared residuals for the regression in Equation (6) as γ, shown on the x-axis, changes (the sum of squared residuals for Equation (5) is plotted at $\gamma = 0$). The sum of squared residuals is minimized when $\gamma = 496.55$. We test for the identity between parameters above and below the threshold, or, equivalently, for the presence of the threshold, $H_0: \ \beta_0 = \tilde{\beta}_0, \ \beta_1 = \tilde{\beta}_1$ and, since the test statistic asymptotic distribution is non-pivotal, we

[21] One variable that could also affect the inventory levels of market makers (e.g., through the risk management practices of dealer desks), and therefore market liquidity, is the volatility of the bond yield. In Section Int.4 of the internet appendix, we repeat the analysis including this variable and our results are robust to this inclusion. Moreover, we also test whether the *CDS Spread* drives both changes in market liquidity and bond return volatility or whether the effects are the other way around, and show that it is the former relation that prevails, confirming that the analysis we perform in this section is correct and robust to the insertion of volatility into the pool of endogenous variables.

bootstrap it, as described in Hansen (1996). The test statistic for the presence of the threshold we observe (25.05) is significant at better than the 1% level, thus confirming the presence of a threshold.[22]

Insert Figure 5 here.

While the previous paragraphs confirm the presence and location of the threshold, $\hat{\gamma} = 496.55$ bp, Figure 6 shows the test statistic needed to determine the confidence bounds around the point estimate we find. The threshold has a point estimate of 496.55, with a 5% confidence interval between 485 and 510, and is almost identical for various alternative specifications of the relation (including whether or not lagged or macro variables are included).

Insert Figure 6 here.

The confirmation of the presence of a structural shift in the data when the CDS spread crosses a certain threshold is, therefore, robust and strongly supported by the data, and indicates how important the level of the *CDS Spread* is for market liquidity.

This result confirms Empirical Prediction 2, and shows that the rules adopted by the clearing house to set margins as a function of the level of the CDS spread have an impact on the relation between credit risk and market liquidity. The application of the margin setting rule is shown in Figure 7, which depicts the time-series of bond-market bid-ask spread, CDS spread, and the average margin on Italian bonds with between 3 months and 30 years to maturity, charged by a major clearing house, Cassa Compensazione e Garanzia, which uses the same margins as those charged by LCH.Clearnet. The margin requirements changed only slightly between June 2010 and November 2011, from 3.26% to 4.53%, while the CDS spread rose threefold from about 150 bp to 450 bp. However, the same clearing house nearly doubled the margins to slightly below 9% on November 9, 2011, the second time the spread hits and stays consistently above 500 bp: in the sovereign risk framework, distributed by the LCH.Clearnet in October 2010 (see LCH.Clearnet, 2011), one of the indicators used to justify a hike in margin is indeed "a 500bp 5 year CDS spread".

It is important to stress that market participants were aware of the rule adopted by the clearing house, which had already enforced this margin setting rule for Irish sovereign bond on November 17, 2010, when the margins on repo transactions were raised from 16-18% to 31-33%. In that instance, LCH.Clearnet argued that this decision had been taken "in response to the sustained period during which the yield differential of 10 year Irish government debt against a AAA benchmark has traded consistently over 500 bp."[23]

Insert Figure 7 here.

[22]The histogram of the bootstrapped test distribution for this and similar tests referred to throughout the paper can be found in the internet appendix, Section Int.6.

[23]Source: http://www.lchclearnet.com/risk_management/ltd/margin_rate_circulars/repoclear/2010-11-17.asp and http://ftalphaville.ft.com//2010/11/17/407351/dear-repoclear-member/

The very day that the clearing houses changed the margins charged on sovereign bonds, their market liquidity suddenly worsened, corresponding to a shift in the level of the bid-ask spread, as predicted by Equation (3) in our model. Brunnermeier and Pedersen (2009) derive a similar prediction, that an increase in margins has an effect on the security's market liquidity, if the market makers' budget constraint is binding. As Figure 3 Panel (c) shows, the CCBSS, measuring the funding liquidity needs of the market makers, was at its highest during the second half of 2011, when the margin changes took place. We interpret our findings as a confirmation of Brunnermeier and Pedersen (2009): In the second half of 2011, when the funding liquidity of the market makers was at its lowest and their budget constraint was binding, a change in the margins charged on sovereign bonds led to a tightening of their market liquidity.

Having now identified the presence of a threshold and the effect that it has on the level of bid-ask spread, we need to determine how the *sensitivity* of market liquidity to credit risk is modified when the threshold is breached. Panel B of Table IV reports the results for Equation (6), when $\gamma = \hat{\gamma}$, or the threshold is the point estimate found in the previous paragraphs, what we call for simplicity the 500 bp threshold. The column "Test" in Panel B reports the test statistic for whether each pair of parameters above and below the threshold is equal; e.g., the test statistic for H0: $\beta_0 = \tilde{\beta}_0$ is 11.33, significant at the 1% level.

As the panel shows, the relationships below and above 500 bp are rather different from each other: contemporaneous changes in the *CDS Spread* have a significantly larger economic impact on market liquidity above the threshold of 500 bp than below. In particular, the regression in Panel B indicates that the coefficient of the contemporaneous change below the threshold is 0.32, but not significant, while that above it is 2.85 and statistically significant. Looking at the lagged CDS variable, we find that, below the 500 bp threshold, market liquidity reacts with a lag to changes in the *CDS Spread*, with a significant impact of the autoregressive component and the lagged component of the change in the CDS. Above 500 bp, the relation is rather different: market liquidity reacts immediately to changes in the *CDS Spread*, with the impact being largely contemporaneous, since the change in the CDS spread has no impact on the change in the market liquidity the following day. The parameters suggest that an increase in the *CDS Spread* of 10% on day t, below (above) the threshold of 500 bp, induces a contemporaneous increase in the *Bid-Ask Spread* of 3.2% (28.5%) on day t, and an increase (decrease) of $-0.332 \cdot 3.2\% + 9.83\% = 8.77\%$ ($-0.332 \cdot 28.5\% - 8.54\% = -18\%$) on day $t + 1$, for a cumulative increase of 11.96% (10.46%). Although the cumulative $t + 1$ effects of a 10% increase in CDS spread are similar above and below the 500 bp threshold, the dynamics of the system are very different: Above 500 bp, the market overreacts by increasing the bid-ask spread instantaneously, while below 500 bp the market reacts moderately, and with a lag, to the increase in credit risk.

The results that we derive in this sub-section for market-wide measures are confirmed by the robustness analysis we perform in Section VII.A, where we group bonds with similar maturities, as determined by counterparty clearing houses with regard to margin requirements, and repeat the analysis regressing each group maturity on the corresponding maturity CDS spread.

Our conclusion, therefore, is that Empirical Prediction 2 is verified and that the dynamic relation between credit risk and market liquidity differs depending on the level of the CDS spread; specifically, in a stressed environment, credit shocks have an immediate impact on market liquidity.[24]

VI.C Policy Intervention and Structural Breaks

Our third empirical prediction is that the various interventions that occurred during the period could have generated a structural break in the relation between credit risk and market liquidity. Therefore, the third research aim of this paper is to examine whether such a structural break can be detected statistically and related to policy changes. Again, we let the data alert us to the presence of a structural break over time.

Empirical Prediction 3 *The monetary policy interventions of the central bank affect the dynamic relation between credit risk and market liquidity.*

As we have described above, the period that we investigate has been characterized by many events: the onset of the Euro-zone sovereign debt crisis, several sovereign credit downgrades, a political crisis that induced changes in Euro-zone governments, and several interventions by European central banks, and, in particular, by the ECB. Of course, by virtue of its status as the central bank of the Euro-zone, the ECB has a major influence on its sovereign bond markets. As described in Section III, the ECB's monetary intervention takes many forms, ranging from formal guidance by its board members, in particular its president, to the injection of liquidity into the major banks in the Euro-zone, which themselves hold these bonds, to direct purchases of sovereign bonds in the cash markets.

The purpose of this section is not to quantify the direct effect of these interventions on the Euro-zone credit risk (see Eser and Schwaab, 2013), or its bond market liquidity (see Ghysels, Idier, Manganelli, and Vergote, 2014), but to examine whether the relation between credit risk and liquidity was significantly altered by one or more of these interventions, as exemplified in the theoretical model presented above, by testing for the presence of a structural break. The scant public availability of data concerning the quantity, issuer nationality, and timing of purchases of bonds in the SMP framework prevents us from quantifying the specific effect of those purchases. Similarly, in the absence of details of the extent of banks' access to LTRO funding and its usage, we are unable to investigate how the refinancing operation affected liquidity provision by the market makers (most of which belong to major international and national banks). However, since the

[24] Since we have determined the presence of parameter discontinuity, we should verify how that discontinuity affects the lead-lag relation investigated in Empirical Prediction 1 for the two samples. Our analysis shows that the same result applies whether the CDS level is below or above the threshold, as shown in Section Int.7 of the internet appendix.

several interventions and policy-relevant events took place over finite and non-overlapping periods of time, we can investigate econometrically whether a structural break in the relation between the two variables of interest occurred around the time of the announcement or implementation of the interventions. This analysis is relevant for our second empirical prediction for two main reasons: first, because if the data indeed exhibit structural breaks, our results will be biased if we ignore them, and second, because it will shed light on the relevant combination of conditions that affects the relation between credit risk and liquidity.

We investigate Empirical Prediction 3 by performing the "structural change breaks" test proposed by Andrews (1993) (the *supF* test in that paper), on Equation (6), the details of which are presented in Appendix B. Briefly, the test corresponds roughly to a Chow (1960) test but, while in the Chow test the structural change break is specified exogenously, this "structural change break" allows us to leave the structural break date unknown *a priori*. The test corresponds to performing a Chow test for the relation in question on each date in the sample. The date that is most likely to constitute a break in the data sample is found endogenously, identified as the date with the largest Chow test value, and the presence of a break itself is tested by comparing that date's (Chow) F-test statistic to a non-standard distribution. The test, therefore, verifies whether there is a structural break, at all, in the specified relation. If the null hypothesis of "no structural break" can be rejected, the date with the largest corresponding Chow test statistic will be selected as the structural break. Figure 8 shows the values of the Chow F-test statistic calculated on each date, with the horizontal line showing the confidence band for the highest F-value.

We find that, from a statistical perspective, the test indicates a break, on December 21, 2011, for the relation between the *Bid-Ask Spread*, and the *CDS Spread*, its lag, and the macro variables, and that this structural break is significant at the 10% level. Although December 21 is identified purely based on the statistical evidence as the date for which the (Chow) *supF* test is most significant for the relevant relationships between the *Bid-Ask Spread* and the *CDS Spread*, it coincides *exactly* with the date of the allotment and the day before the settlement of the LTRO program by the ECB.[25]

Our evidence suggests that the relation between credit risk and liquidity changed when the ECB provided LTRO funding to the banks. To the extent that the relation measures the sensitivity of the market makers' behavior to changes in the (credit) risk of their portfolios, our finding supports our empirical prediction, that the market makers were wary about providing liquidity to the sovereign bond market.

They were particularly concerned that, should an adverse credit event have occurred, their inventory would have suffered and they would have been left with no available funding liquidity. The large provision of funding from the ECB constituted a structural break in that relation and had a clear impact on the sensitivity of market makers to changes in the credit riskiness of their

[25]The policy implementation announcement of December 8, 2011 with all the important dates for this measure can be found online at `http://www.ecb.europa.eu/press/pr/date/2011/html/pr111208_1.en.html`

inventories, as we quantify in the following paragraphs.

In order to account for this structural break in our estimations, we split the sample into two periods, and again perform the threshold test as per Equation (6) in both subsamples. That is, we test whether the relation between the changes in the bid-ask spread, and the changes in the CDS spread and its lag, varies above and below an endogenously found threshold. The bootstrap procedure for the threshold test confirms the presence of different relationships below and above the threshold level of 500 bp for the CDS spread, in the first subsample (July 1, 2010 to December 21, 2011), but fails to identify a threshold for the second subsample. Figure 9 reports the test to identify confidence bands around the threshold point estimates, for the first and second subsample, in Panel (a) and (b), respectively: the threshold can be identified around 500 bp for the first subsample, while no threshold can be found in the second subsample.

This result suggests that, thanks to the assurance of a massive amount of liquidity from the ECB and the ECB's request to the clearing house to avoid the possibility for margins to become procyclical to sovereign risk, the relation between changes in the CDS spread and market liquidity was not altered when the Italian CDS Spread breached the level of 500 bp after the LTRO intervention, in contrast to the period before the intervention.

Insert Figure 8 here.

Insert Figure 9 here.

Panel A of Table V presents the results of the estimation for the first subsample, before December 21, 2011, and confirms the results we presented above. The main difference is that, for the split sample, the relation between the change in the *CDS Spread* and market liquidity, when the *CDS Spread* is above 500 bp, is even stronger in the pre-LTRO regime, with a 10% increase in the *CDS Spread* translating into a 39% contemporaneous increase in the *Bid-Ask Spread*.

Insert Table V here.

Table V Panel B presents the results of the estimation for the second subsample, after December 21, 2011, and shows that the presence of the autoregressive component in market liquidity is still apparent. However, the contemporaneous relation between changes in the *CDS Spread* and changes in market liquidity is no longer significant, while there is a lagged adjustment of market liquidity related to changes in the *CDS Spread* on the previous day, with an economic intensity that is smaller that in the full sample reported in Table IV, Panel A (0.566 vs. 0.794), and about a half of the corresponding parameter for the 2011 subsample, when the CDS is below 500 bp, reported in Table V Panel A (0.566 vs. 1.028). Moreover, our analysis shows that the global risk variable, USVIX, affects market liquidity only for the 2011 subsample, while, after the ECB intervention, the only significant variable is the funding liquidity measure, CCBSS.

The previous literature (e.g., Eser and Schwaab, 2013; Ghysels, Idier, Manganelli, and Vergote,

2014) shows that the SMP had an effect on the yields of the bonds chosen for the program, following the large buying pressure exerted by the central bank purchases. However, to the extent that the risk levels of the market makers were maintained, the relation between credit risk and liquidity would have remained unaltered. Hence, the SMP, which was implemented in 2010, did not, in fact, constitute a structural break for that dependence. The LTRO, on the contrary, constituted a massive intervention targeting the availability of funding liquidity and, as such, was ideal for affecting how the banks disposed of their available capital, making them less sensitive to changes in credit risk, when providing liquidity to the market. We tested whether other structural breaks would emerge from the data after December 21, 2011, and no date emerged as statistically significant.

It is worth stressing that, although margins were increased again in June, July, and August 2012 (in August to the same level as in November 2011), Figure 7 shows that the market illiquidity did not increase then as it did in November 2011, as a result of the hike in margins, but rather stayed constant. The large infusion of funding liquidity resulting from the LTRO, confirmed by the low levels of CCBSS after January 2012 shown in Figure 3 Panel (c), loosened the market makers' funding constraints, so that, consistent with Brunnermeier and Pedersen's (2009) prediction, we show empirically that the change in margins in 2012 did not affect the market makers' provision of market liquidity, since their budget constraints were not binding.

The results of the analysis of the structural break in the time series confirm what we posited in Empirical Prediction 3 and allow us to argue that LTRO intervention was very effective in severing the strong connection between credit risk and market liquidity. It is interesting to observe that both the SMP and LTRO interventions generated injections of liquidity into the system by the ECB. However, the magnitudes were completely different (€103 billion in August 2011 versus €489 billion in December 2011) and so were the mechanisms: in the first case, the ECB bought the sovereign bonds directly, while, in the second case, it provided money to reduce the funding liquidity constraints of the banks, which perhaps used some of the released liquidity to purchase sovereign bonds.

VII Robustness Checks

VII.A Results for Bonds with Different Maturities

In the body of the paper, we report the results based on the daily bid-ask spread, obtained from MTS data by averaging the quoted bid-ask spread on a bond-day basis, and then averaging them across bonds. The reader may wonder about the robustness of our results with regard to the data composition. One direction for investigating the robustness of the results is that of exploiting the cross-section of bonds. In fact, the liquidity of bonds with different maturities could relate to the CDS spread of corresponding maturity in different ways: Prices of short-term bonds are less sensitive to changes in credit risk and, similarly, their relevance for inventory concerns and

VaR considerations should be mitigated by their short time-to-maturity. To characterize the heterogeneity of the effect of credit risk on market liquidity with respect to bond maturity, we split the bonds into different maturity groups and investigate whether i) the effects of credit risk on liquidity are smaller for shorter maturity bonds and ii) our main results hold similarly for all maturity groups.[26]

We consider 11 maturity buckets, based on the classification used by Cassa Compensazione e Garanzia when setting margins. Bonds are grouped together daily if they have the following time-to-maturity: from 0 to 1 month, from 1 to 3 months, from 3 to 9 months, from 9 months to 1.25 years, from 1.25 to 2 years, from 2 to 3.25 years, from 3.25 to 4.75 years, from 4.75 to 7 years, from 7 to 10 years, from 10 to 15 years, and finally from 15 to 30 years. We calculate a liquidity measure per group-day by averaging the bid-ask spreads of the bonds in each group. For each day, we interpolate the CDS spread curve provided by Markit for the Italian sovereign entity and extract, per each maturity bucket, the CDS spread for a contract that has maturity equal to the average between the lower and higher maturity boundaries, e.g., we interpolate the CDS curve, obtain the spread for the 4-year maturity contract and attribute it to the bucket including bonds with 3.25 to 4.75 years to maturity. Due to the lack of a CDS spread estimate for maturities below 3 months, we drop the observations for the first two groups. Table VI reports the average bid-ask spread and CDS spread, together with the correlations between changes in the two variables, for each maturity group. The illiquidity measure is decreasing in time-to-maturity, with the exception of the 10-year benchmark bonds in group 9.

Insert Table VI here.

Panel (a) of Figure 10 reports the evolution of the (log-) bid-ask spreads for the nine remaining maturity buckets from July 1, 2010 to December 2012, while Panel (b) reports the term structure of (log-) CDS spread for the nine corresponding maturities. Figure 11 shows the margin evolution for each maturity bucket. Panel (a) of Figure 10 shows that the liquidity series for different maturities comoved to a very large extent, and so did the CDS spreads in Panel (b). Moreover, when the 5-year CDS contract reached 500 bp (6.215 on the y-axis), the term structure became flat, so that all CDS contracts exhibited a spread above 500 bp, regardless of their maturity. That is exactly the time when the clearing houses raised their margins for all maturities, as shown in Figure 11.

Insert Figure 10 here.

Insert Figure 11 here.

We first perform a pooled OLS panel regression corresponding to Equation (5), with the changes in the bid-ask spreads for maturity group g on day t, $\Delta BA_{g,t}$, as the dependent variable and

[26]We thank the anonymous referee for suggesting we pursue this direction in our analysis.

changes in CDS contracts for maturity g on day t, $\Delta CDS_{g,t}$, as regressors, allowing the coefficients to differ across maturities:

$$\begin{aligned}\Delta BA_{g,t} &= \alpha + \sum_{i=1}^{3} \alpha_i \Delta BA_{g,t-i} + \beta_{0g} \Delta CDS_{g,t} \\ &\quad + \beta_{1g} \Delta CDS_{g,t-1} + \beta_2 \Delta CCBSS_t + \beta_3 USAVIX_t + \epsilon_t. \end{aligned} \tag{7}$$

The results for Equation (7) are reported in Table VII Panel A. The table shows that the changes in the bid-ask spread for all the maturities are positively related to changes in the CDS contracts with one lag, so that the results for the average of the bid-ask spread reported above are confirmed. Moreover, the coefficients are increasing with maturities up to the 8th bucket, so that the effects of credit risk on illiquidity are smaller for shorter maturities. However, the parameters for longer maturities are decreasing. At least for bucket 9, we can attribute this effect to the fact that the 10-year bond is the most liquid bond, and has a lower bid-ask spread than the other maturities, while instead the term structure of CDS has a positive slope most of the time.

Insert Table VII here.

We investigate whether the result regarding the threshold level of 500 bp for the 5-year CDS contract CDS_t is confirmed, when we allow maturity groups to have different sensitivities to their corresponding CDS spread. We thus estimate Equation (8):

$$\begin{aligned}\Delta BA_{g,t} &= \alpha + \sum_{i=1}^{3} \alpha_i \Delta BA_{g,t-i} + I\left[CDS_t < \gamma\right] \left(\beta_{0g} \Delta CDS_{g,t} + \beta_{1g} \Delta CDS_{g,t-1}\right) \\ &+ I\left[CDS_t > \gamma\right] \left(\tilde{\beta}_{0g} \Delta CDS_{g,t} + \tilde{\beta}_{1g} \Delta CDS_{g,t-1}\right) + \beta_2 \Delta CCBSS_t + \beta_3 USAVIX_t + \epsilon_t. \end{aligned} \tag{8}$$

The test statistic for the presence of the threshold has an estimate of 78.9 and is significant at the 1% level. Figure 12 shows that the results regarding the shift in the relation between the bid-ask and CDS spread, when the CDS spread crosses 500 bp, is confirmed. Therefore, the threshold effect we find for the market-wide bid-ask spread measure is the same for all maturities, as expected given that the term structure of the CDS spread is flat above 500 bp and all margins change significantly when the CDS cross the 500 bp level.[27]

Insert Figure 12 here.

The results of the panel regression for the subsamples in which the 5-year CDS spread is above and below 500 bp are reported in Table VII Panel B. The results confirm those obtained in the previous sections for the market-wide bid-ask spread measure: below 500 bp, the relation with the

[27] In Section Int.6 of the internet appendix we estimate Equation (8) separately for each maturity group, i.e., we estimate Equation (6) for each maturity bucket, and we show that the same threshold is present in *all* maturity buckets.

lagged changes in the CDS is positive and significant, while when the CDS spread is above the threshold it is the contemporaneous change in credit risk that is significant. In summary, our main results hold when we group bonds in maturity buckets, providing robustness to the main results of the paper.

VII.B Results for Different Liquidity Measures

In the main body of the paper, we conducted the analyses focusing on a single measure for the (il)liquidity of the bond market, the *Bid-Ask Spread*, since it is both the most familiar and most indicative of market conditions. As a final robustness effort, and since there is no consensus in the academic or policy-making literatures regarding the best metrics for assessing the liquidity of an asset, using a shorter data set, we repeat our regressions for the other liquidity measures that have been used extensively in the literature. We establish, in Section Int.8 of the internet appendix, that our results are robust to the choice of liquidity measure.[28]

VIII Conclusion

The sovereign debt crisis in the Euro-zone has been the most important development in the global economy in the past five years. The crisis stemmed from both liquidity and credit risk concerns in the market and led to a sharp spike in CDS and sovereign bond yield spreads in late 2011, particularly in the Euro-zone periphery. It was only after the launch of the LTRO program and after Mario Draghi's "whatever it takes" comment in July 2012 that the market's alarm diminished: CDS spreads and sovereign bond yields had dropped to sustainable levels in most Euro-zone countries by late 2012. Hence, there is no doubt, *prima facie*, that the ECB programs were a crucial factor in, at least partially, abating the crisis.

These events provide us with an unusual laboratory in which to study how the interaction between credit risk and illiquidity played out, in a more comprehensive framework than has been used in previous studies of corporate or other sovereign bond markets, for the reasons we highlighted in the introduction. We investigate several hypotheses about the main drivers of the *dynamic relation* between credit risk and market liquidity, controlling for global systemic factors and funding liquidity. We conclude that credit risk was one of the main driving forces in determining the liquidity of the bond market, based on a Granger-causality analysis aimed at investigating whether liquidity risk drives credit risk or vice versa. We verify the robustness of our results by testing the same hypothesis in a panel-data setting, and by repeating the analysis using other liquidity measures. In addition to the specific Italian sovereign risk, other global factors such

[28]The bid-ask spread is correlated by more than 60% with other liquidity variables, making it an appropriate representation of market liquidity. Pelizzon, Subrahmanyam, Tomio, and Uno (2013) study several liquidity proxies in the context of the cross-section of the Italian sovereign bonds.

as the USVIX and the funding liquidity measure CCBSS are relevant to the dynamics of market liquidity.

A second important finding is that, prior to ECB intervention, the relation between credit risk and market liquidity was strong, and depended not simply on the changes in credit risk, but also on the *level* of credit risk. Using an econometric methodology that allows us to identify the threshold above which the relation is altered, we estimate that this level corresponds to a CDS spread of 500 bp. This break point of 500 bp is employed in the setting of margin requirements, which fundamentally alters the relation between changes in credit risk and market liquidity. We link our findings to the growing literature on funding liquidity, providing a fitting example of the Brunnermeier and Pedersen (2009) theoretical prediction on the effect of funding liquidity on market liquidity.

We also examine the improvement in market liquidity following the intervention by the ECB. Our analysis indicates that there is a clear structural break following the allotment and settlement of the LTRO on December 21, 2012. Remarkably, the data show that, following the ECB intervention, the improvement in funding liquidity available to the banks strongly attenuated the dynamic relation between credit risk and market liquidity. Although the CDS spread breached the 500 bp mark and margins were raised once again, market liquidity and the relation between credit risk and market liquidity did not change significantly between the regimes below and above this level. Actually, the only variable that still has an impact on market liquidity after the ECB intervention is the global funding liquidity variable, CCBSS. Thus, the ECB intervention not only vastly improved the funding liquidity of the market, but also substantially loosened the link between credit risk and market liquidity.

Our results will be of interest to the Euro-zone national treasuries, helping them to understand the dynamic nature of the relation between credit risk, funding liquidity, and market liquidity, which has strong consequences for the pricing of their issues in the auctions as well as in secondary markets. The ECB may also derive some insights from our analysis that could help them to better understand the impact of the unconventional instruments of new monetary policy. Apart from targeting both funding and market liquidity, the central bank ought also to focus on the market's perceptions of sovereign credit risk.

Appendix A: The Model

In this Appendix, we present our theoretical model in detail and make explicit the steps leading to the results reported in Section III. In our model, the market maker (dealer) has an investment account, holding other securities, and a trading account, holding the bond in which she is making a market. At time t, the initial wealth W_0 is split between the investment account and the trading account, while the remainder, when positive, is invested in the risk free rate.[29] If the dealer does not trade during the period, at the end of the time interval t to $t+1$, the terminal wealth of her initial portfolio will be

$$W_I = W_0 k\,(1 + r_M) + I\,(1 + r) + (W_0\,(1 - k) - (1 - M_I)\,I)\left(1 + B_I + r_f\right),$$

where k is the fraction of her wealth invested in her preferred portfolio with (expected) return r_M ($\overline{r_M}$), I is the true dollar value of current inventory of the stock with (expected) net return r ($\overline{r}$) and variance σ^2, r_f is the (net) risk free rate over the interval. In this appendix, we make use of indicator functions to simplify the exposition, so that $B_I = bi(W_0\,(1-k) - (1 - M_I)\,I < 0)$, where i is the indicator function, equals $b > 0$ (0), when the cash position $W_0(1-k) - (1 - M_I)\,I$ is negative (positive), due to borrowing costs, and $M_I = mi(I < 0)$, due to margins. All returns are assumed to be normally distributed. The borrowing rate is higher than the lending rate and equal to $r_b = r_f + b$.

To better understand the wealth equation, let us consider the following examples (the chosen parameters being $\overline{r_M} = 10\%$, $r_f = 5\%$, $\gamma = 1$, $\sigma_M^2 = 1$, $W_0 = 1000$, $k = \frac{\overline{r_M} - r_f}{\gamma W_0 \sigma_M^2} = \frac{5\%}{1000} = 0.005\%$):

Case 1: $I = 500$ is invested in the inventory. The market maker is long in the bond, and so no margins have to be taken into consideration; moreover, her total cash position is positive, and hence no borrowing is needed.

$$W_I = 1000 \cdot k \cdot (1 + r_M) + \underbrace{500 \cdot (1 + r)}_{\text{Inventory position}} + \left((1 - k)\,1000 - \underbrace{500}_{\substack{\text{Cash paid}\\\text{to the customer}}}\right) \cdot (1 + 5\%)$$

Case 2: $I = 1500$ is invested in the inventory. She is long in the bond, so no margins have to be taken into consideration, however her total cash position is negative, so she needs to borrow at the central bank's lending facilities, where she pledges the bond as collateral. There, she can borrow the full amount, but, however, she will have to pay an interest rate

[29]We do not use the time subscript, t, in the following, to avoid clutter in the notation.

$r_b = r_f + b > r_f$

$$W_I = 1000 \cdot k \cdot (1 + r_M) + \underbrace{1500 \cdot (1 + r)}_{\text{Inventory position}} + \left((1 - k)\, 1000 - \underbrace{1500}_{\substack{\text{Cash paid} \\ \text{to the customer}}} \right) \cdot \left(\underbrace{1 + b + 5\%}_{\text{Cost of borrowing}} \right)$$

Case 3: $I = -500$, and thus, she is short 500 worth of the bond. She adds to her cash position $(1 - m)\, 500$, because of her short position in the bond (inventory). She borrows the bond at a cost that is a fraction m of the face value.

$$W_I = 1000 \cdot k \cdot (1 + r_M) - \underbrace{500 \cdot (1 + r)}_{\text{Inventory position}} + \left(\begin{array}{l} (1 - k)\, 1000 + \overbrace{500}^{\substack{\text{Cash received} \\ \text{from the customer}}} \\ - \underbrace{m500}_{\substack{\text{Cost of borrowing the specific} \\ \text{bond, paid upfront}}} \end{array} \right) \cdot (1 + 5\%)\,.$$

The dealer trades so that her expected utility from maintaining the time-0 portfolio, or trading the dollar quantity Q, are equal, with the post trading wealth being

$$\begin{aligned} W_{I+Q} =& W_0 k \,(1 + r_M) + (I + Q)\,(1 + r) \\ &+ \left(W_0\,(1 - k) - (1 - M_{I+Q})\,(I + Q)\right) \cdot \left(1 + B_{I+Q} + r_f\right) + C\left(1 + r_f\right), \end{aligned}$$

where C is the dollar cost of entering into this transaction, and the last term includes the cost of carrying the inventory (profit from borrowing out) in case of a buy (sell) trade. These costs can be positive or negative, depending on whether the trade in the stock raises or lowers the dealer's inventory holding costs, and essentially capture the dealer's exposure cost of holding a non-optimal portfolio. The indicator functions $B_{I+Q} = bi(W_0 - kW_0 - (1 - M_{I+Q})\,(I + Q) < 0)$ and $M_{I+Q} = mi(I + Q < 0)$ serve the same purpose of B_I and M_I. She will trade if

$$E\left[U\left(W_I\right)\right] = E\left[U\left(W_{I+Q}\right)\right]. \tag{9}$$

The market maker is assumed to have a constant absolute risk-aversion utility function $U(x) = -e^{-\gamma x}$. The marginal condition in Equation (9) implies that the relative cost of trading for a quantity Q is

$$\begin{aligned} \frac{C_Q}{Q} =& \frac{\gamma\left(\frac{Q}{2} + I\right)\sigma^2 - (1 + \bar{r}) + \gamma k W_0 \sigma_{iM}}{1 + r_f} + \frac{I}{Q}\left[\begin{array}{l} (1 - M_{I+Q})\,\frac{1 + B_{I+Q} + r_f}{1 + r_f} \\ -(1 - M_I)\,\frac{1 + B_I + r_f}{1 + r_f} \end{array} \right] \\ &+ \frac{W_0}{Q}\,(1 - k)\,\frac{B_I - B_{I+Q}}{1 + r_f} + (1 - M_{I+Q})\,\frac{1 + B_{I+Q} + r_f}{1 + r_f}, \end{aligned}$$

where $\sigma_{iM} = COV[r_M, r]$ is the covariance between the bond and the market returns. We add the subscript in C_Q to highlight the dependence of C on Q. The dealer chooses k optimally so that, when $I = 0$, $\frac{\partial W_I}{\partial k} = 0$, or $k = \frac{\overline{r_M} - r_f}{\gamma W_0 \sigma_M^2}$.[30] The choice of k, together with the mean-variance capital asset pricing model (CAPM) portfolio equilibrium condition $\overline{r} - r_f = \left(\overline{r_M} - r_f\right) \frac{\sigma_{iM}}{\sigma_M^2}$, allows us to rewrite $\frac{C_Q}{Q}$ as

$$
\begin{aligned}
\frac{C_Q}{Q} =& \frac{\gamma\left(\frac{Q}{2} + I\right)\sigma^2 - \left(1 + r_f\right)}{1 + r_f} + \frac{I}{Q}\left[\begin{array}{c} (1 - M_{I+Q})\frac{1 + B_{I+Q} + r_f}{1 + r_f} \\ -(1 - M_I)\frac{1 + B_I + r_f}{1 + r_f} \end{array}\right] \\
&+ \frac{W_0}{Q}(1 - k)\frac{B_I - B_{I+Q}}{1 + r_f} + (1 - M_{I+Q})\frac{1 + B_{I+Q} + r_f}{1 + r_f}.
\end{aligned}
$$

The relative bid ask spread for a dollar quantity $|Q| > 0$ is the summation (since they are signed quantities) between buying a stock from the market maker at the ask price $-|Q| + C_{-|Q|}$ (i.e., the price at which the market maker sells $|Q|$), and selling it at the bid price $|Q| + C_{+|Q|}$, so that the relative bid-ask spread becomes

$$
\frac{-|Q| + C_{-|Q|} + |Q| + C_{+|Q|}}{|Q|} = \frac{C_{+|Q|} + C_{-|Q|}}{|Q|} = \frac{C_{+|Q|}}{|Q|} - \frac{C_{-|Q|}}{-|Q|}.
$$

We restrict our attention to the case when the market maker incurs costs both when she accumulates a long and a short position, i.e., $B_{I+|Q|} = b$, $B_{I-|Q|} = B_I = 0$ and $M_{I-|Q|} = m$, $M_{I+|Q|} = M_I = 0$. Moreover, we assume that $I = 0$, and the two components of the relative bid-ask spread for a quantity $|Q|$ become

$$
\begin{aligned}
\frac{C_{+|Q|}}{|Q|} &= \frac{\left(\begin{array}{c} \gamma\frac{|Q|}{2}\sigma^2 - \left(1 + r_f\right) \\ -\frac{W_0}{|Q|}(1 - k)b + 1 + b + r_f \end{array}\right)}{1 + r_f} = \frac{\gamma\frac{|Q|}{2}\sigma^2}{1 + r_f} + \frac{b}{1 + r_f}\frac{|Q| - W_0(1 - k)}{|Q|} \\
\frac{C_{-|Q|}}{-|Q|} &= \frac{\left(\begin{array}{c} \gamma\frac{-|Q|}{2}\sigma^2 - \left(1 + r_f\right) \\ +(1 - m)\left(1 + r_f\right) \end{array}\right)}{1 + r_f} = -\frac{\gamma\frac{|Q|}{2}\sigma^2}{1 + r_f} - m.
\end{aligned}
$$

Finally, the absolute bid-ask, calculated as the relative bid-ask spread for purchasing a quantity $Q = p_0$ multiplied by the price of the bond p_0, is

$$
BA = \frac{\gamma p_0^2 \sigma^2}{1 + r_f} + m p_0 + b\frac{p_0 - W_0(1 - k)}{1 + r_f}. \tag{10}
$$

[30] We follow Stoll (1978) and assume that the market maker chooses the fraction of her wealth invested in the market portfolio before building an inventory.

The Option

Since the default of a sovereign is, at least partly, a political decision, we take the approach of looking at the underlying process as merely that, rather than an endogenous choice of the "equity holders". We can think of a CDS contract as sort of an event-triggered put option written on the sovereign bond.[31] Brennan (1979) and Stapleton and Subrahmanyam (1984) show that a sufficient condition for a risk-neutral valuation of a contingent claim when the price of the underlying asset is assumed to be normally distributed is that the utility function of the representative investor be exponential (Theorem 6). Therefore, the price of a put option with strike k at time t, if the price of the underlying p is normally distributed $N(\overline{p}, \sigma_p^2)$, with $p = p_0(1+r)$, $\overline{p} = p_0(1+\overline{r})$, and $\sigma_p^2 = p_0^2\sigma^2$, would be

$$CDS = \frac{1}{1+r_f} \int_{-\infty}^{+x} (x-p) \frac{1}{\sigma_p\sqrt{2\pi}} \cdot \exp\left(-\frac{1}{2\sigma_p^2}\left(p - \left(1+r_f\right)(1-m)\,p_0\right)^2\right) dp$$

and, with a change of variable to $z = \frac{p-\left(1+r_f\right)(1-m)p_0}{\sigma_p}$

$$CDS = \left(\frac{x-\left(1+r_f\right)(1-m)\,p_0}{1+r_f}\right) \cdot N\left(\frac{x-\left(1+r_f\right)(1-m)\,p_0}{\sigma_p}\right) + \frac{\sigma_p}{1+r_f} n\left(\frac{x-\left(1+r_f\right)(1-m)\,p_0}{\sigma_p}\right),$$

where N and n are the cumulative and standard normal distribution functions, respectively.

If we consider a margin-adjusted at-the-money put option, i.e., one such that $x = \left(1+r_f\right)(1-m)\,p_0$, the CDS price formula simplifies to $CDS = \frac{\sigma p_0}{1+r_f} n\,(0)$, so that the market maker extracts the volatility from the CDS market according to a simple linear approach:

$$\sigma = \left(1+r_f\right)\frac{CDS}{p_0 n\,(0)}. \tag{11}$$

Empirical Predictions

Re-writing the absolute bid ask spread in Equation (10) as a function of the CDS price, and plugging Equation (11) into 10, we obtain the relation between the depending variable of interest, the bid-ask spread, and its determinants, the CDS spread, and the policy quantities set by clearing houses and the central bank:

$$BA(CDS) = \delta CDS^2 + m\,(b, CDS)\,p_0 + b\eta, \tag{12}$$

[31]This is not literally correct, given that the CDS is triggered by an event, rather than by exercise at expiration, but is useful here as a simplification, to avoid the need to model the default intensity process

where $\frac{\gamma(1+r_f)}{n(0)^2} = \delta > 0$ and $\frac{p_0 - W_0(1-k)}{1+r_f} = \eta > 0$ and, where, realistically, we allow the margin setting decision by the clearing house to depend on both the level of the CDS spread and the borrowing rate set by the central bank.[32, 33] From Equation (12), we obtain the following empirical predictions, which we discuss in Section III.A:

Empirical Prediction 1 *The illiquidity of the bond market increases with credit risk.*

Empirical Prediction 2 *The dynamic relation between credit risk and market illiquidity shifts conditional on the level of the CDS spread.*

Empirical Prediction 3 *The monetary policy interventions of the central bank affect the dynamic relation between credit risk and market liquidity.*

An Implicit Formulation

Similar implications can be derived from Equation (10) even without the assumption that the market maker uses the simple linear approach in Equation (11). Indicating the relation between the CDS price and the return volatility that is extracted from it by $\sigma^2(CDS)$, Equation (10) becomes

$$BA = \frac{\gamma p_0^2}{1 + r_f}\sigma^2\left(CDS\right) + m\left(b, CDS\right)p_0 + b\eta$$

and the same empirical predictions follow.

[32]We refer to CDS price, in the theoretical section, and CDS spread, in the rest of the paper, interchangeably.

[33]The second inequality follows from the assumption that the market maker borrows the funds necessary to buy a bond by pledging the latter at the central bank. That is, $B_{I+|Q|} = b$, meaning that $(1-k)W_0 - (1 - M_{I+|Q|})(I + |Q|)) < 0$, which corresponds to the inequality, when we assume that $I = M_{I+|Q|} = 0$, and that the trade occurs for a quantity $|Q| = p_0$.

Appendix B: Methodological Appendix

Threshold Analysis

In empirical settings, a regression such as the OLS specification $y_i = \beta' x_i + e_i$, where y_i is the dependent variable that is regressed on the independent variable x_i, is often repeated for subsamples, either as a robustness check or to verify whether the same relation applies to appropriately grouped observations. The sample split is often conducted in an exogenous fashion, thus dividing the data according to the distribution of a key variable, such as size and book-to-market quantile portfolios in a Fama-French (1993) setting. Hansen (1996, 2000) develops the asymptotic approximation of the distribution of the estimated threshold value $\hat{\gamma}$, when the sample split, based on the values of an independent variable q_i, can be rewritten as

$$Y = X\theta + X_\gamma \delta + e \qquad \text{where } X_\gamma = XI(q \leq \gamma)$$

or $y_i = \theta' x_i + \delta I(q_i \leq \gamma) x_i + e_i$, where $I(q_i \leq \gamma)$ equals 1 if $q_i \leq \gamma$, and 0 otherwise. He shows that, under a set of regularity conditions, which exclude time-trending and integrated variables, the model can be estimated by least squares, minimizing $SSR_n(\theta, \delta, \gamma) = (Y - X\theta - X_\gamma \delta)'(Y - X\theta - X_\gamma \delta)$.[34] Concentrating out all parameters but γ, i.e. expressing them as functions of γ, yields $S_n(\gamma) = SSR_n(\hat{\theta}(\gamma), \hat{\delta}(\gamma), \gamma) = Y'Y - Y'X^*_\gamma('X^*_\gamma{}'X^*_\gamma)^{-1} X^*_\gamma{}'Y$ with $X^*_\gamma = \left[X \; X_\gamma\right]$. The parameters θ and δ are formulated as functions of γ, and the sum of squared residuals depends exclusively on the observed variables and on γ. Thus, the value of γ that minimizes $S_n(\gamma)$ is its least squares estimator $\hat{\gamma}$, and the estimators of the remaining parameters $\hat{\theta}(\hat{\gamma})$ and $\hat{\delta}(\hat{\gamma})$ can be calculated.

When there are N observations, there are at most N values of the threshold variable q_i, or equivalently N values that the $SSR(\gamma)$ (step-)function can take. After re-ordering the values q_i in $(q_{(1)}, q_{(2)}, ...q_{(N)})$, such that $q_{(j)} \leq q_{(j+1)}$, the method is implemented by

1. estimating by OLS $y_i = \theta_2' x_i + \delta I(q \leq q_{(j)}) x_i + e_i$ (or equivalently, when all parameters are allowed to depend on the threshold, estimating separately $y_i = \theta_1' x_i + e_{1i}$ where $q_i \leq q_{(j)}$ and $y_i = \theta_2' x_i + e_{2i}$ where $q_i > q_{(j)}$),

2. calculating the sum of squared residuals, $SSR(q_{(j)}) = \sum e_i$ (or $= \sum e_{1i} + \sum e_{2i}$),

3. repeating 1 and 2 with $q_{(j+1)}$,

4. finding the least squares estimate of γ as $\hat{\gamma} = \arg\min_{q_{(j)}} S(q_{(j)})$, and

5. repeating the estimation of the equations on the subsamples defined by the $\hat{\gamma}$ threshold, calculating heteroskedasticity-consistent standard errors for the parameters.

[34] A theory for the latter case was developed in Caner and Hansen (2001).

As suggested by Hansen (1999), we allow each equation to contain at least 20% of the observations, and, to minimize computing time, we search only through 0.5%-quantiles. Although Hansen (1999) presents an extension of the procedure to several thresholds, we focus in this paper on a single sample split.

To test the presence of the threshold, thus testing whether $\theta_1 = \theta_2$, the usual tests cannot be used, since γ is not identified under the null hypothesis. This is known as the "Davies' Problem", as analyzed by Davies (1977, 1987). Hansen (1996) provides a test whose asymptotic properties can be approximated by bootstrap techniques.

To provide confidence intervals for the threshold estimate $\hat{\gamma}$, Hansen (2000) argues that no-rejection regions should be used. To test $\gamma = \gamma_0$, the likelihood ratio test can be used such that $LR(\gamma) = (SSR(\gamma) - SSR(\hat{\gamma}))/\hat{\sigma}^2$, where $\hat{\sigma}^2 = SSR(\hat{\gamma})/N$ is the estimated error variance, will be rejected if $\hat{\gamma}$ is sufficiently far from γ, i.e., the test statistic is large enough. In its homoskedastic version, the test has a non-standard pivotal distribution, such that the test is rejected at an α-confidence level if $LR(\gamma) > -2\ln(1-\sqrt{\alpha})$. In this paper, we choose $\alpha = 0.95$, consistent with Hansen (2000); thus, the null hypothesis is considered rejected if $LR(\gamma) >= -2\ln(1-\sqrt{0.95}) = 7.35$. This level is plotted as a horizontal line in the plots of the test. The confidence interval for the threshold will be $[\gamma_L, \gamma_U]$, such that $LR(\gamma\,|\gamma < \gamma_U) > 7.35$, and $LR(\gamma\,|\gamma > \gamma_U) > 7.35$, or, graphically, the portion of the x-axis in which the plot of the test is below the 7.35 horizontal line.

Structural Break Tests

The Chow test is a standard break point analysis used widely in the economics literature. Based on two nested regressions, it follows an $f_{k,T-2k}$-distribution and its statistic is

$$F = \frac{(SSR_0 - SSR_1)/k}{SSR_1/(T-2k)}.$$

where SSR_0 and SSR_1 are the sum of squared residuals of the restricted regression, $y_t = x_t'\beta + \epsilon_t$ (with $t = 1, \ldots, T$), and the unrestricted regression, $y_t = x_t'\beta + g_t x_t'\gamma + \epsilon_t$, respectively. In the unrestricted regressions, the observations following the break point t^*, selected by the dummy variable g_t (such that $g_t = 1$ if $t < t^* \leq T$ and 0 otherwise), are allowed to depend on x_t through the composite parameters $\beta + \gamma$, while the previous observations depend on x_t through β only. The restriction $\gamma = 0$ thus imposes the condition that all y_t depend on x_t in a homogeneous fashion.[35]

A drawback of the Chow test is that the breakpoint has to be specified exogeneously. The Chow test has a null hypothesis, which is that the parameters after a specific date are equal to those that generated the data before the break date. The alternative hypothesis is that the two sets of parameters are indeed different. However, a test statistic can be calculated from the statistics resulting from the Chow test, the Fs, to test whether a structural break took place at an *unknown*

[35]We exclude the first and last 10% of the observations, in order to estimate meaningful regressions.

date. After the F-statistics have been computed for a subset of dates, e.g., all the dates in the sample except for the first and last i%, several test statistics can be calculated from them.

Andrews (1993) and Andrews and Ploberger (1994) show that the supremum and the average, respectively, of the F-statistics converge to a pivotal non-standard distribution, depending on the number of parameters tested and the relative number of dates tested. The test statistics that we calculate to test for a structural break at an unknown date are therefore

$$supF = \sup_t F_t$$
$$aveF = \frac{\sum_t F_t}{T},$$

where the F_t are found using the Chow test estimation. We then compare the $supF$ and $aveF$ test statistics with the corresponding confidence levels, that can be found in Andrews (2003), which rectified those tabulated in Andrews (1993), and Andrews and Ploberger (1994).

Tables

Table I
Maturity and *Coupon Rate* by Maturity Group and Bond Type.

This table presents the distribution of the bonds in the sample in terms of *Maturity* and *Coupon Rate*, by maturity group (Panel A) and bond type (Panel B). Maturity groups were determined by the time distance between bond maturities and the closest whole year. Our data set, obtained from the Mercato dei Titoli di Stato (MTS), consists of transactions, quotes, and orders for all 189 fixed-rate and floating Italian sovereign bonds (Buoni Ordinari del Tesoro (BOT) or Treasury bills, Certificato del Tesoro Zero-coupon (CTZ) or zero-coupon bonds, Certificati di Credito del Tesoro (CCT) or floating notes, and Buoni del Tesoro Poliennali (BTP) or fixed-income Treasury bonds) from July 1, 2010 to December 31, 2012. All bonds in the groups marked with (a) are BOT, Buoni Ordinari del Tesoro (Treasury bills), all bonds in the groups marked with (b) are CTZ, Certificati del Tesoro Zero-coupon (zero-coupon bonds), and all bonds in the groups marked with (c) are CCT, Certificati di Credito del Tesoro (floating bonds)

Panel A					
Maturity Group	# Bonds	Coupon Rate	Maturity	MinMaturity	MaxMaturity
0.25	11.000	(a)	0.260	0.210	0.270
0.50	38.000	(a)	0.500	0.360	0.520
1.00	44.000	(a)	1.000	0.810	1.020
2.00	13.000	(b)	2.020	2.010	2.090
3.00	14.000	3.380	2.980	2.930	3.020
5.00	16.000	3.860	5.020	4.920	5.250
6.00	15.000	(c)	6.710	5.210	7.010
10.00	21.000	4.540	10.440	10.100	10.520
15.00	7.000	4.590	15.710	15.440	16.000
30.00	10.000	5.880	30.880	30.000	31.790

Panel B					
Bond Type	N	Coupon Rate	Maturity	MinMaturity	MaxMaturity
BOT	93.000	ZCB	0.710	0.210	1.020
BTP	68.000	4.340	11.120	2.930	31.800
CCT	15.000	Floating	6.710	5.210	7.010
CTZ	13.000	ZCB	2.020	2.000	2.090

Table II

Time-series Descriptive Statistics of the Variables.

This table shows the time-series and cross-sectional distribution of various variables defined in Section IV.A, and their correlations. The sample consists of the quotes and trades from 641 days in our sample for bond market data and end-of-day quotes for the other measures. *Quoted Bonds* is the number of bonds actually quoted on each day, *Trades* is the total number of trades on the day, and *Volume* is the daily amount traded in € billion on the whole market. The liquidity measure *Bid-Ask Spread* is the difference between the best bid and the best ask. The global systemic variables are the spread between three-month Euribor and three-month German sovereign yield, the USVIX, and the Cross-Currency Basis Swap Spread CCBSS. Our bond-based data, obtained from the Mercato dei Titoli di Stato (MTS), consist of transactions, quotes, and orders for all 189 fixed-rate and floating Italian sovereign bonds (Buoni Ordinari del Tesoro (BOT) or Treasury bills, Certificato del Tesoro Zero-coupon (CTZ) or zero-coupon bonds, Certificati di Credito del Tesoro (CCT) or floating notes, and Buoni del Tesoro Poliennali (BTP) or fixed-income Treasury bonds) from July 1, 2010 to December 31, 2012. All other data were obtained from Bloomberg. *** indicate significance at the 1% level.

	Time Series					Unit Root Test	
Panel A: Market Measures							
Variable	Mean	STD	5th Pct	Median	95th Pct	Level	Difference
Quoted Bonds	88.583	2.430	85.000	88.000	93.000v		
Trades	352.158	149.394	145.000	331.000	614.000		
Volume	2.874	1.465	0.951	2.555	5.647		
Panel B: System Variables							
Bid-Ask Spread	0.389	0.340	0.128	0.298	1.092	−8.200***	−32.597***
Italian CDS	320.748	137.834	149.356	302.026	540.147	−1.469	−19.922***
USVIX	21.212	6.302	15.070	18.970	34.770	−3.951***	−26.790***
CCBSS	44.003	18.915	21.100	39.900	79.400	−1.613	−25.969***
Euribor-DeTBill	0.729	0.357	0.264	0.629	1.474	−1.750	−31.843***
Panel C: Correlations							
Differences\Levels	Bid-Ask Spread	Italian CDS	USVIX	CCBSS	Euribor -DeTBill		
Bid-Ask Spread	1.000	0.628	0.440	0.659	0.676		
Italian CDS	0.224	1.000	0.318	0.788	0.589		
USVIX	0.151	0.334	1.000	0.511	0.660		
CCBSS	0.182	0.367	0.233	1.000	0.842		
Euribor-DeTBill	0.049	0.088	0.050	0.054	1.000		

Table III

Results for the Granger-Causality Analysis of the Italian CDS Spread and Bid-Ask Spread.

This table presents the results for the regressions of the day t changes in *Bid-Ask Spread*, ΔBA_t, and Italian CDS spread ΔCDS_t, on the lagged terms of both variables and on contemporaneous macro variable changes, in a VARX(3,0) setting as shown in Equation (4). The data have a daily frequency. The significance refers to heteroskedasticity-robust t-tests. Heteroskedasticity-robust F-test statistics and their significance are reported for the null hypothesis of $\Delta BA_t = \Delta BA_{t-1} \ldots = 0$ ($BA \xrightarrow{GC} CDS$), and $\Delta CDS_t = \Delta CDS_{t-1} \ldots = 0$ ($CDS \xrightarrow{GC} BA$) respectively. We also report the contemporaneous correlation in the model residuals. Our data set consists of 641 days of trading in Italian sovereign bonds, from July 1, 2010 to December 31, 2012, and was obtained from the MTS (Mercato dei Titoli di Stato) Global Market bond trading system. The CDS spread refers to a USD-denominated, five-year CDS spread. The CDS spread and the macro variables were obtained from Bloomberg. $*$, $**$, and $***$ indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Variable	ΔBA_t	ΔCDS_t
ΔBA_{t-1}	−0.357***	−0.011
ΔCDS_{t-1}	0.917***	0.212***
ΔBA_{t-2}	−0.224***	−0.007
ΔCDS_{t-2}	−0.069	−0.091*
ΔBA_{t-3}	−0.174***	−0.004
ΔCDS_{t-3}	0.117	0.024
$\Delta EuriborDeTBill_t$	0.027	0.035
$\Delta CCBSS_t$	0.545***	0.213***
$\Delta USVIX_t$	0.334**	0.154***
Intercept	−0.001	0.001
Adj R^2	0.180	0.236
Granger-Causality Tests		
$BA \xrightarrow{GC} CDS$		0.476
$CDS \xrightarrow{GC} BA$	6.007***	
Residuals Correlation		
ΔBA_t	1.000	0.107
ΔCDS_t	0.107	1.000

Table IV

Results for the Regression of the Bid-Ask Spread on the CDS Spread and Macro Variables.

This table presents the results for the regression of the change in the *Bid-Ask Spread* (the change in the quoted bid-ask spread) on day t, ΔBA_t, on its lagged terms, and the change in the CDS spread on day t, ΔCDS_t, and its lagged terms and on macro variables, using daily data. The regressions are presented in Equations (5) and (6), for Panels A and B, respectively. Parameters multiplying the identity operator $[CDS \leq (>)500]$ are reported under the $[CDS \leq (>)500]$ column. The statistical significance refers to heteroskedasticity-robust t-tests. The Test column reports the heteroskedasticity-robust test for the two parameters above and below the threshold being equal and distributed as chi-square (1). Our data set consists of 641 days of trading in Italian sovereign bonds, from July 1, 2010 to December 31, 2012, and was obtained from the Mercato dei Titoli di Stato (MTS) Global Market bond trading system. The CDS spread refers to a USD-denominated, five-year CDS spread and macro variables were obtained from Bloomberg. $*$, $**$, and $***$ indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Variable	Panel A	Panel B		
	Whole Sample	I[CDS≤500]	I[CDS>500]	Test
ΔCDS_t	0.541**	0.319	2.845***	11.330***
ΔCDS_{t-1}	0.794***	0.983***	−0.854*	10.750***
ΔBA_{t-1}	−0.352***	-0.332***		
ΔBA_{t-2}	−0.216***	-0.199***		
ΔBA_{t-3}	−0.167***	-0.164***		
$\Delta CCBSS_t$	0.429***	0.402***		
$\Delta USVIX_t$	0.251*	0.208*		
Intercept	−0.002	-0.002		
Adj R^2	0.191	0.219		
N	637	637		

Table V

Results for the Regression of the Bid-Ask Spread on the CDS Spread and Macro Variables for Subsamples Based on the Structural Break.

This table presents the results for the regression of the change in the *Bid-Ask Spread* (the change in the quoted bid-ask spread) on day t, ΔBA_t, on its lagged terms, and the change in the CDS spread on day t, ΔCDS_t, and its lagged terms, using daily data for the *Bid-Ask Spread* and the CDS spread. The regressions are presented for Equations (6) and (5) in Panels A and B respectively. Parameters multiplying the identity operator $[CDS \leq (>)500]$ are reported under the $[CDS \leq (>)500]$ column. The statistical significance refers to heteroskedasticity-robust t-tests. The Test column reports the heteroskedasticity-robust test results for the two parameters above and below the threshold being equal and distributed as chi-square (1). Panel A (B) is based on the pre-(post-)structural-break sample. Our data set consists of 641 days of trading in Italian sovereign bonds, from July 1, 2010 to December 31, 2012, and was obtained from the Mercato dei Titoli di Stato (MTS) Global Market bond trading system. The CDS spread refers to a USD-denominated, five-year CDS spread and macro variables were obtained from Bloomberg. $*$, $**$, and $***$ indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Variable	Panel A: 2011			Panel B: 2012
	I[CDS≤500]	I[CDS>500]	Test	
ΔCDS_t	0.493	3.877***	16.210***	0.064
ΔCDS_{t-1}	1.028***	−1.491**	11.770***	0.566**
ΔBA_{t-1}	-0.261***			−0.501***
ΔBA_{t-2}	-0.183***			−0.295***
ΔBA_{t-3}	-0.162***			−0.188***
$\Delta CCBSS_t$	0.310*			0.858***
$\Delta USVIX_t$	0.320**			−0.105
Intercept	0.002			−0.006
Adj R^2	0.233			0.237
N	377			260

Table VI
Descriptive Statics for Bonds Grouped by Maturity.

his table presents the time-series average of the bid-ask spread for bonds grouped by their time to maturity, the time-series average of the CDS spread with matching maturity, and the correlation between daily changes in the bid-ask and CDS spreads (contemporaneous, and with a lag). Our data set consists of 641 days of trading in Italian sovereign bonds, from July 1, 2010 to December 31, 2012, and was obtained from the Mercato dei Titoli di Stato (MTS) Global Market bond trading system. The CDS spread refers to a USD-denominated CDS spread with maturity matching the average maturity of the bond group and was obtained from the term structure of the CDS spread provided by Markit.

Maturity Group	Bid-Ask Spread	CDS Spread	Contemporaneous Correlation	Lagged Correlation
03:3-9m	0.142	201.883	0.108	0.090
04:0.75-1.25y	0.198	230.540	0.136	0.137
05:1.25-2y	0.282	255.422	0.148	0.163
06:2-3.25y	0.337	286.799	0.214	0.150
07:3.25-4.75y	0.469	308.557	0.207	0.155
08:4.75-7y	0.519	317.945	0.196	0.167
09:7-10y	0.495	317.701	0.130	0.142
10:10-15y	0.757	315.404	0.121	0.100
11:15-30y	0.958	311.923	0.073	0.093

Table VII

Results for the Regression of the Bid-Ask Spread on the CDS spread and Macro Variables with Maturity-Specific Coefficients.

This table presents the results for the regression of the change in the *Bid-Ask Spread* for maturity group g on day t, $\Delta\text{BA}_{g,t}$, on its lagged terms, and the change in the CDS spread with maturity matching that of group g on day t, $\Delta\text{CDS}_{g,t}$, and its lagged term and on macro variables, using daily data. The regressions presented in Equations (7) and (8) are used for Panels A and C, and for Panel B, respectively. Parameters multiplying the identity operator $[CDS \leq (>)500]$ are reported under the $[CDS \leq (>)500]$ column. The statistical significance refers to heteroskedasticity-robust t-tests. The Test column reports the heteroskedasticity-robust test for the two parameters above and below the threshold being equal and distributed as chi-square (1). Our data set consists of 641 days of trading in Italian sovereign bonds, from July 1, 2010 to December 31, 2012, and was obtained from the Mercato dei Titoli di Stato (MTS) Global Market bond trading system. The CDS spread refers to a USD-denominated CDS spread with maturity matching the average maturity of the bond group and was obtained from the term structure of the CDS spread provided by Markit. $*$, $**$, and $***$ indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Variable	Panel A Whole Sample	Panel B:2011 I[CDS≤500]	I[CDS>500]	Test	Panel C:2012
$\Delta\text{CDS}_{3,t}$	0.247	0.397*	3.776***	17.620***	−43.000
$\Delta\text{CDS}_{4,t}$	0.301	0.403*	3.751***	10.290***	−0.077
$\Delta\text{CDS}_{5,t}$	0.196	0.360	4.085***	21.320***	−0.443*
$\Delta\text{CDS}_{6,t}$	0.372*	0.422	2.763***	7.000***	−0.052
$\Delta\text{CDS}_{7,t}$	0.356	0.501	2.344***	3.850**	−0.292
$\Delta\text{CDS}_{8,t}$	0.275	0.288	2.784***	6.730***	−0.339
$\Delta\text{CDS}_{9,t}$	−0.014	−0.146	2.757***	9.510***	−0.421
$\Delta\text{CDS}_{10,t}$	0.091	0.131	2.827***	5.570**	−0.630*
$\Delta\text{CDS}_{11,t}$	−0.106	−0.147	2.374**	4.610**	−0.624
$\Delta\text{CDS}_{3,t-1}$	0.437***	0.745***	−0.227	2.130	0.032
$\Delta\text{CDS}_{4,t-1}$	0.750***	1.099***	0.349	0.830	0.169
$\Delta\text{CDS}_{5,t-1}$	0.941***	1.144***	−0.277	3.610*	0.594***
$\Delta\text{CDS}_{6,t-1}$	0.944***	1.071***	0.078	2.530	0.745**
$\Delta\text{CDS}_{7,t-1}$	1.066***	1.178***	0.069	2.450	0.939***
$\Delta\text{CDS}_{8,t-1}$	1.197***	1.521***	−0.004	4.600**	0.711**
$\Delta\text{CDS}_{9,t-1}$	0.954***	1.225***	0.291	1.850	0.395
$\Delta\text{CDS}_{10,t-1}$	0.672***	1.092***	−1.554*	9.060***	0.351
$\Delta\text{CDS}_{11,t-1}$	0.624**	0.932**	−1.221	6.210**	0.486
$\Delta\text{BA}_{g,t-1}$	−0.429***	-0.400***			−0.490***
$\Delta\text{BA}_{g,t-2}$	−0.250***	-0.234***			−0.286***
$\text{BA}_{g,t-3}$	−0.159***	-0.168***			−0.140***
ΔCCBSS_t	0.652***	0.515***			1.026***
ΔUSVIX_t	0.315***	0.302***			0.142
Intercept	0.001	0.003			−0.004
Adj R^2	0.190	0.199			0.209
N	7007	4147			2860

Figures

Figure 1
The Dynamics of the Theoretical Model.

This figure shows the channels through which the players in the model are affected by credit risk and by each other.

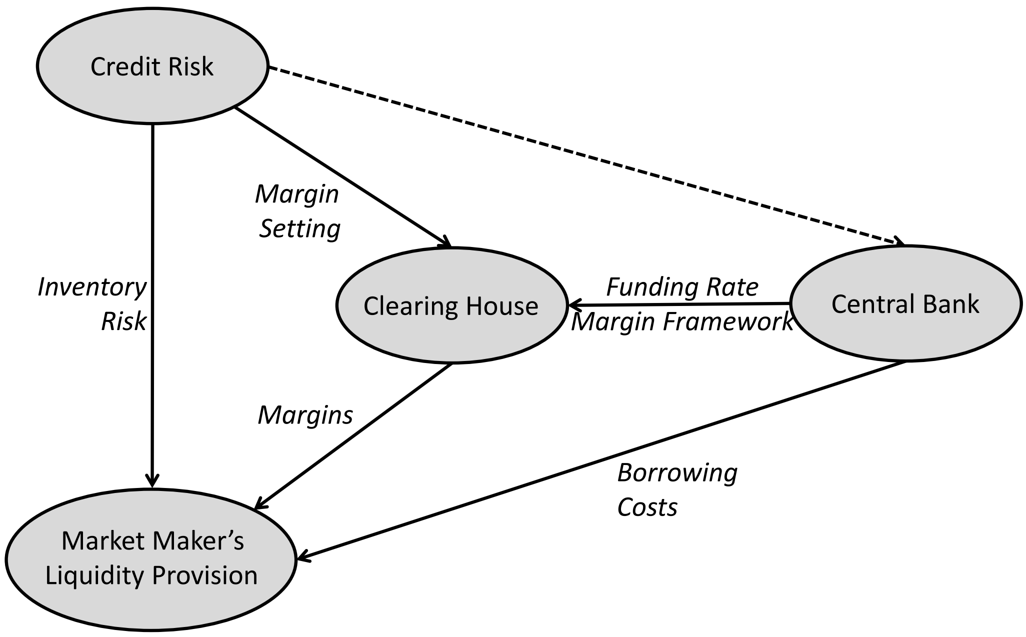


Figure 2
Time-Series of Bond Yield, Bond Yield Spread, CDS Spread, and Bid-Ask Spread.

The bond yield spread (dotdash line, left-hand axis) is calculated between the Italian (dotted, left-hand axis) and German bonds with ten years to maturity. The CDS Spread (solid, left-hand axis) is the spread for a five-year US-denominated CDS contract. This MTS bid-ask spread (dashed, right-hand axis) is a market-wide illiquidity measure. Our data set consists of transactions, quotes, and orders for all 189 fixed-rate and floating Italian sovereign bonds (Buoni Ordinari del Tesoro (BOT) or Treasury bills, Certificato del Tesoro Zero-coupon (CTZ) or zero-coupon bonds, Certificati di Credito del Tesoro (CCT) or floating notes, and Buoni del Tesoro Poliennali (BTP) or fixed-income Treasury bonds) from July 1, 2010 to December 31, 2012. Data for the bond yield, yield spread, and CDS spread were obtained from Bloomberg.

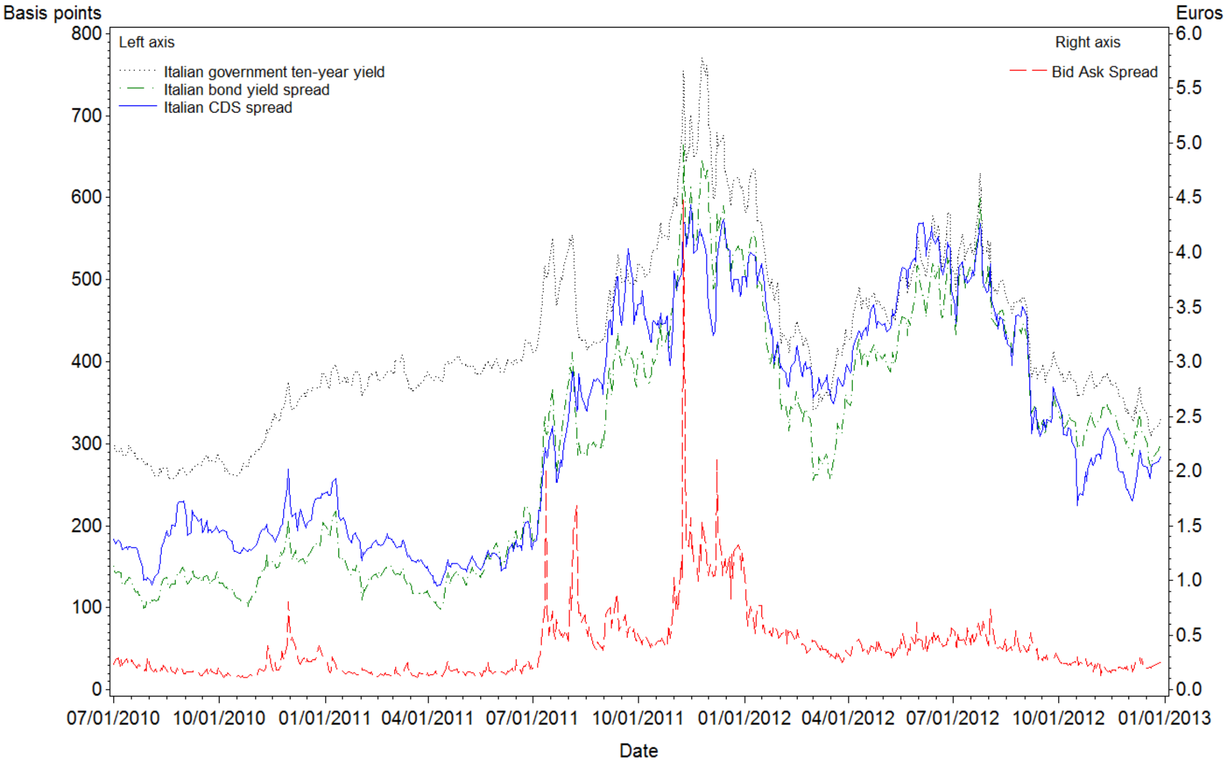
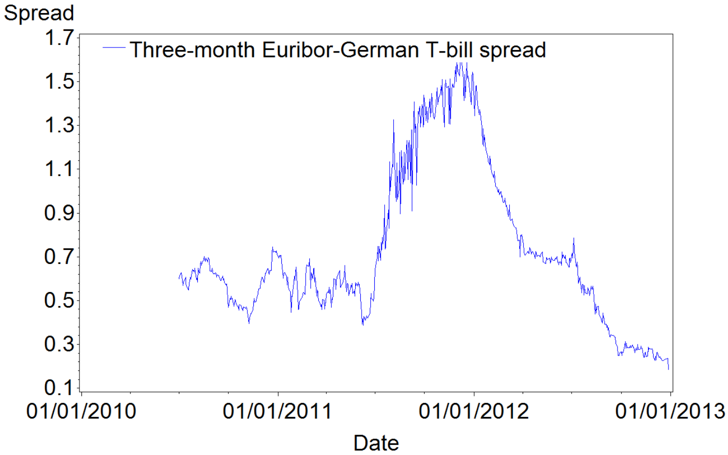


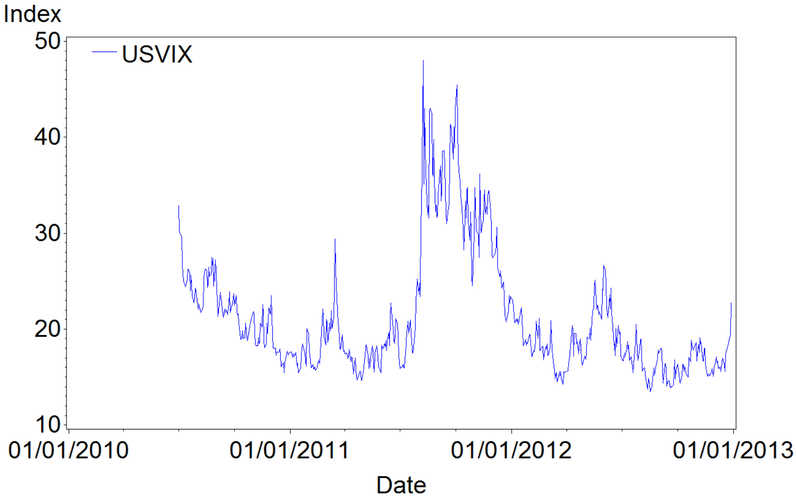
Figure 3
Time-Series of Macro variables.

The time-series evolution of the global variables: the spread between the three-month Euribor and the three-month yield of the German TBill, the USVIX, and the Cross-Currency Basis Swap Spread are shown in Panels (a), (b), and (c), respectively. Global variables are described in detail in Section IV.A. Our data set was obtained from Bloomberg and covers the period from July 1, 2010 to December 31, 2012.

A: 3-Month Euribor-German T-Bill Spreads



B: USVIX Index



C: Cross-Currency Basis Swap Spread

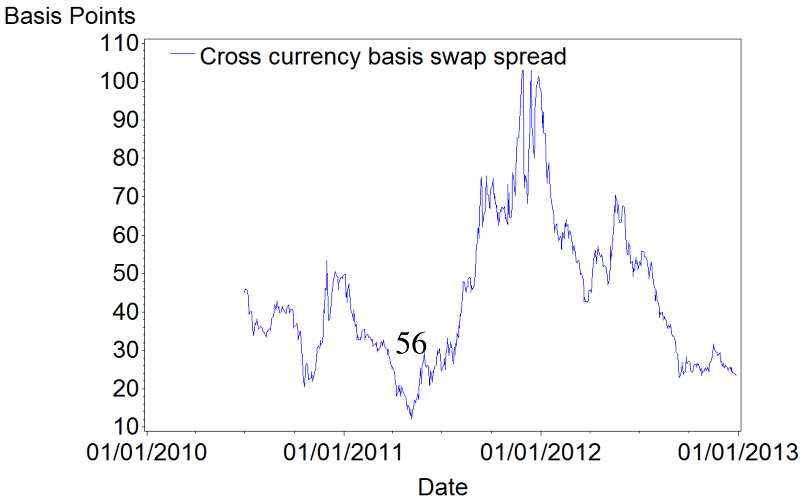
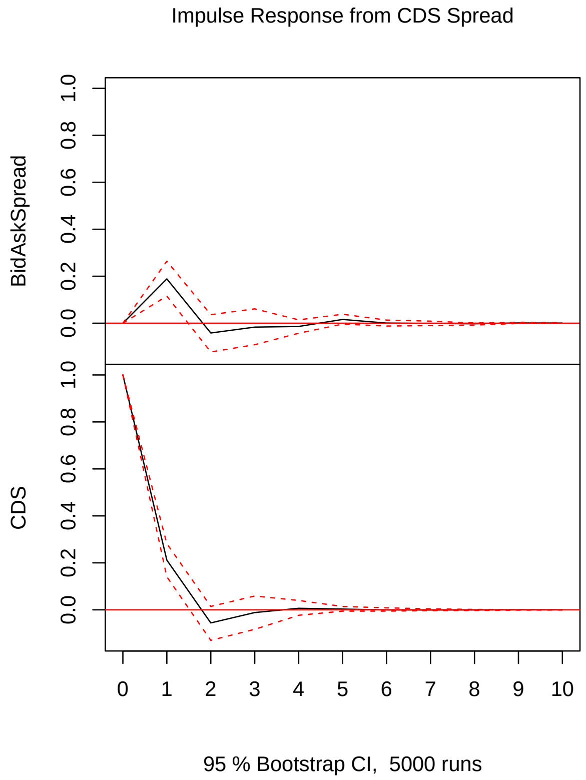


Figure 4
Impulse Response Functions for the VARX(3,0) System.

This graph shows the evolution of the impulse response functions (IRFs) following a shock in the CDS spread and the bond market liquidity, as measured by the Bid-Ask Spread, in Panels (a) and (b) respectively. The VARX(3,0) system that produces these IRFs is presented in Equation (4) and discussed in Section VI.A. Our data set consists of transactions, quotes, and orders for all 189 fixed-rate and floating Italian sovereign bonds from July 1, 2010 to December 31, 2012.

A: Shock to CDS spread



B: Shock to the bond market liquidity

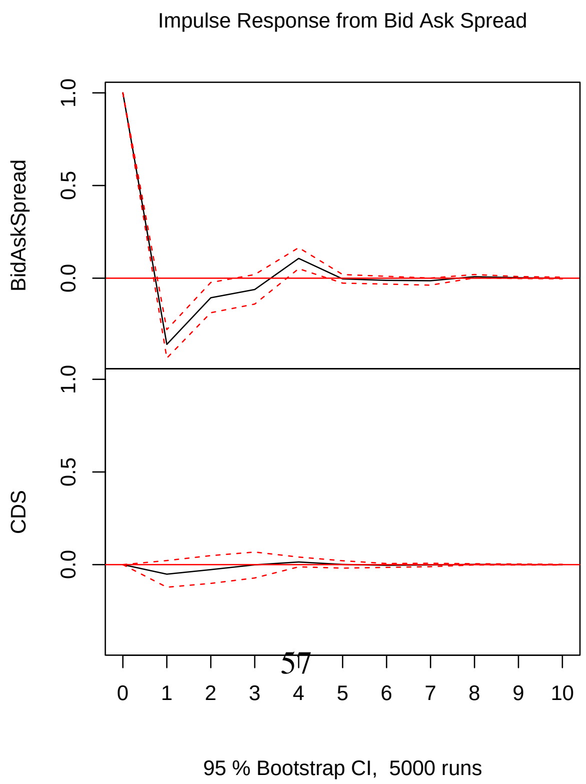


Figure 5
Sum of Squared Residuals as γ Changes.

The evolution of the sum of squared residuals (SSR) from Equation (6) is plotted as the threshold value γ changes. The γ that minimizes SSR ($\hat{\gamma}$) is the estimate for the threshold. The point at $\gamma = 0$ is the SSR for Equation (5), namely the regression with no threshold. Our data set consists of transactions, quotes, and orders for all 189 fixed-rate and floating Italian sovereign bonds, from July 1, 2010 to December 31, 2012.

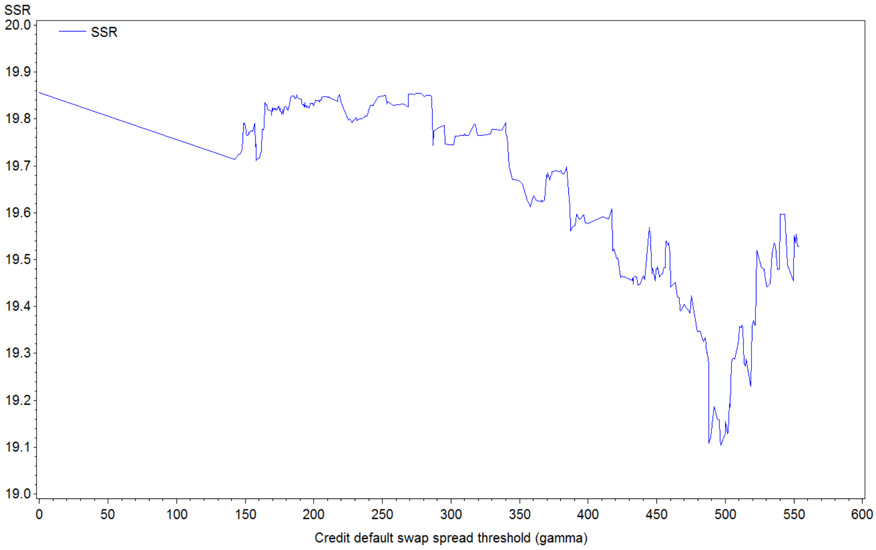


Figure 6
Test to Determine Confidence Bands around the CDS Threshold.

The test statistic described in Appendix B is plotted here for Equation (6). The test statistic is normalized at 0 at the threshold that minimizes the sum of squared residuals. The horizontal line at 7.35 marks the 5% confidence values for the threshold. Our data set consists of transactions, quotes, and orders for all 189 fixed-rate and floating Italian sovereign bonds, from July 1, 2010 to December 31, 2012.

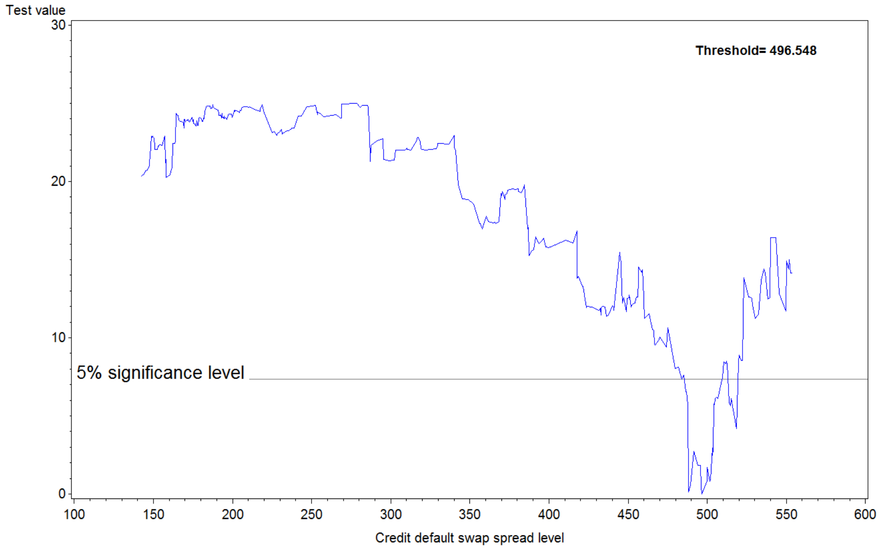


Figure 7
Time-Series of Margins, CDS Spread, and Bid-Ask Spread.

This graph shows the time-series of the average of the margins (dotdashed, left axis) set by Cassa Compensazione e Garanzia, a clearing house, on Italian bonds, the spread of a five-year CDS contract (solid, left axis), and the liquidity of the bond market (dashed, right axis), as measured by the market-wide bid-ask spread. Our data set consists of transactions, quotes, and orders for all 189 fixed-rate and floating Italian sovereign bonds, from July 1, 2010 to December 31, 2012.

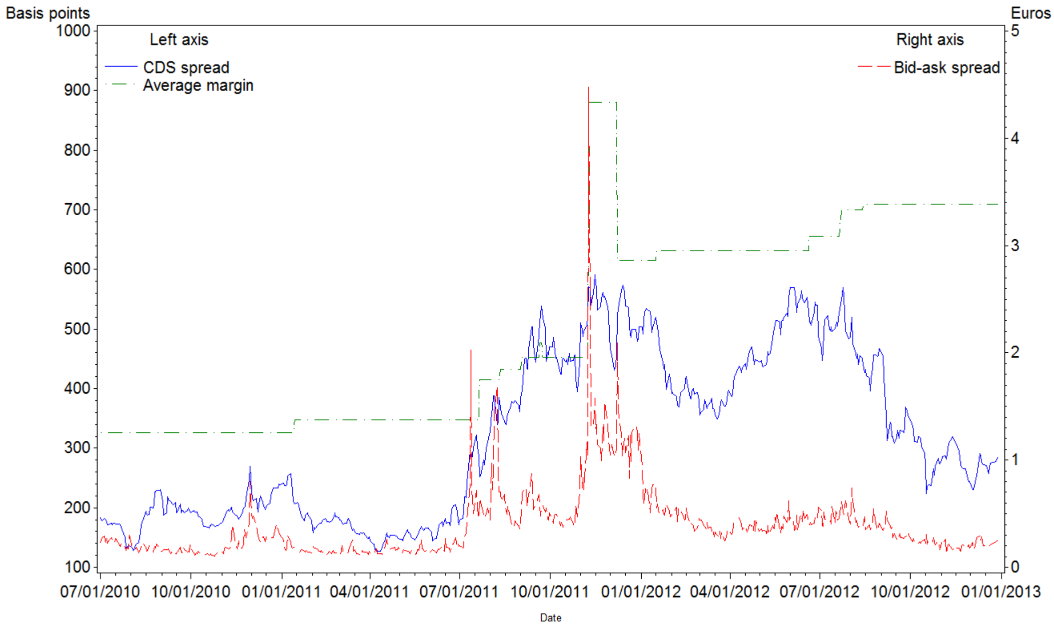


Figure 8
Structural Break Test.

This figure shows the F-test results for the Chow test performed for Equation (6) for each day in our sample, excluding the first and last 20% of observations. The horizontal line marks the 10% level of significance for the largest of the F-test values. Our data set consists of transactions, quotes, and orders for all 189 fixed-rate and floating Italian sovereign bonds, from July 1, 2010 to December 31, 2012. The CDS data were obtained from Bloomberg.

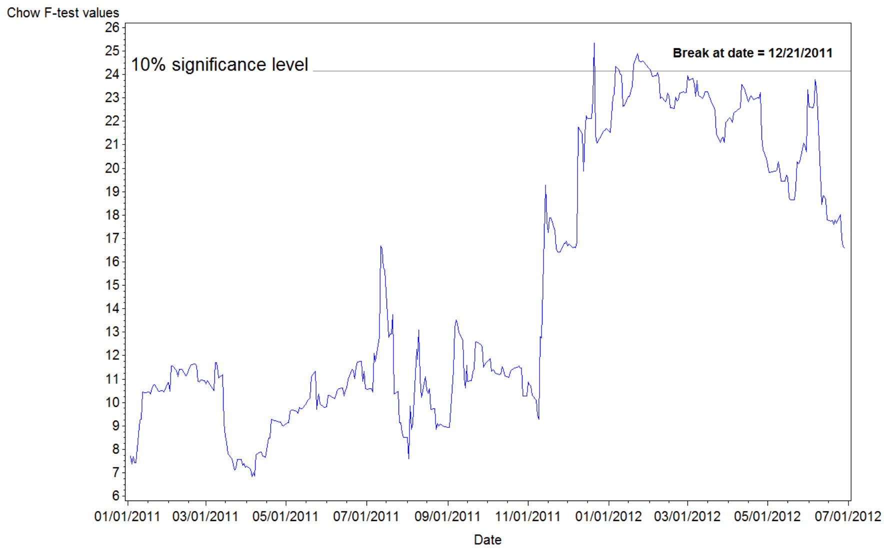
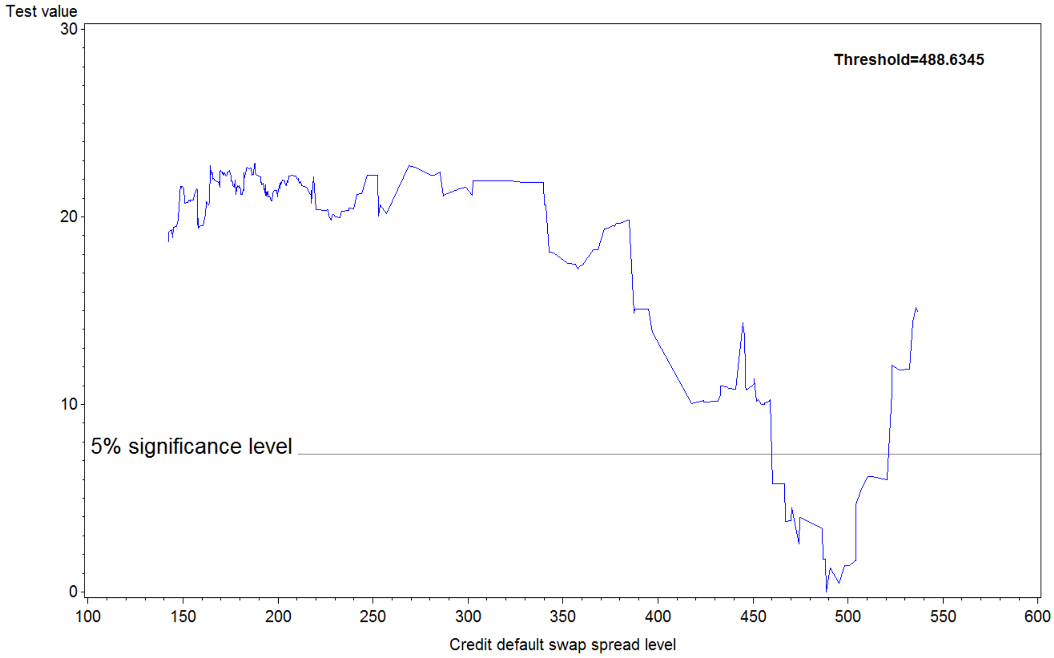


Figure 9
Confidence Bands Determination for Two Subsamples.

The test statistic described in Appendix B is plotted here for Equation (6) in Panels (a) and (b) for the subsamples before and after the structural break, respectively. The test statistic is normalized at 0 at the threshold that minimizes the sum of squared residuals. The horizontal line at 7.35 marks the 5% confidence values for the threshold.

A: Threshold Confidence Bands Determination: 2011 Sample



B: Threshold Confidence Bands Determination: 2012 Sample

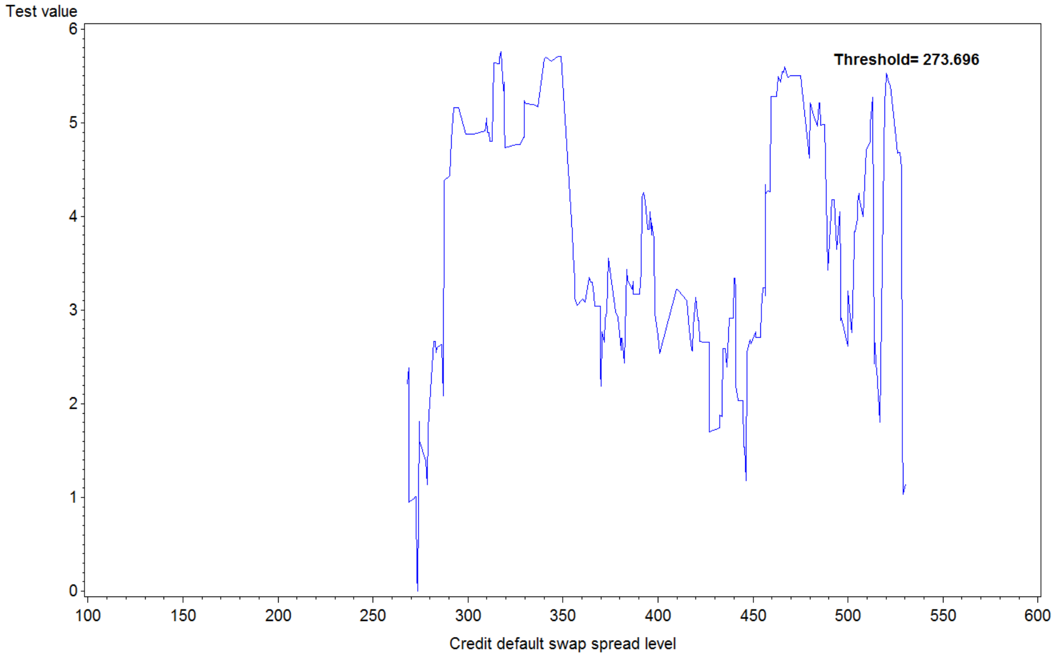
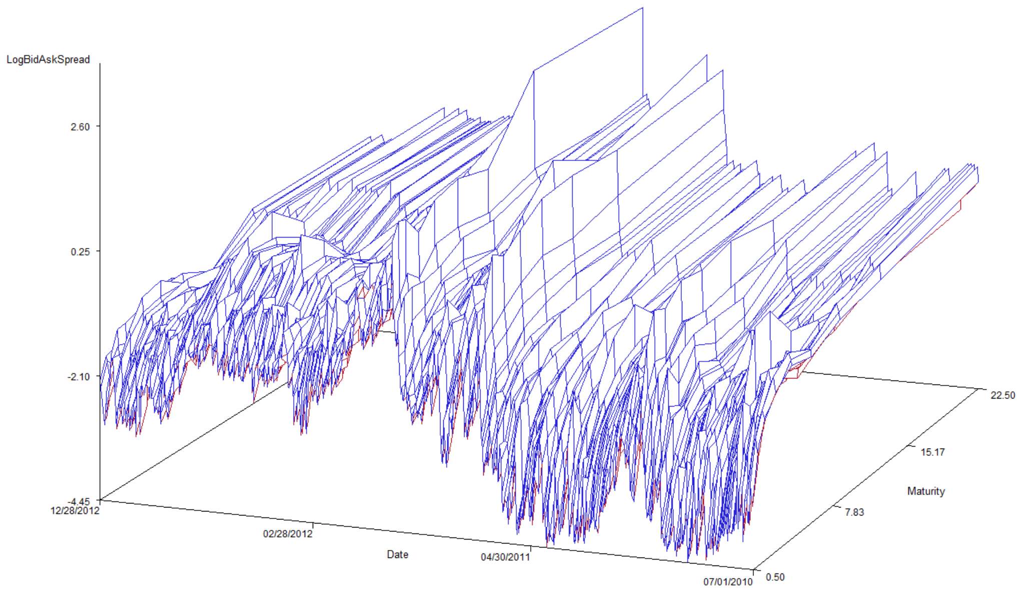


Figure 10
Bid-Ask Spread, CDS Spread, and Maturity.

This figure shows time-series of the log of the average bid-ask spread for bonds as a function of maturity and the time-series of the log of the CDS spread for 9 maturities of the contract, in Panels (a) and (b), respectively. Our data set consists of transactions, quotes, and orders for all 189 fixed-rate and floating Italian sovereign bonds, from July 1, 2010 to December 31, 2012.

A: Bid-Ask Spread Evolution and Maturity.



B: CDS Spread and Maturity.

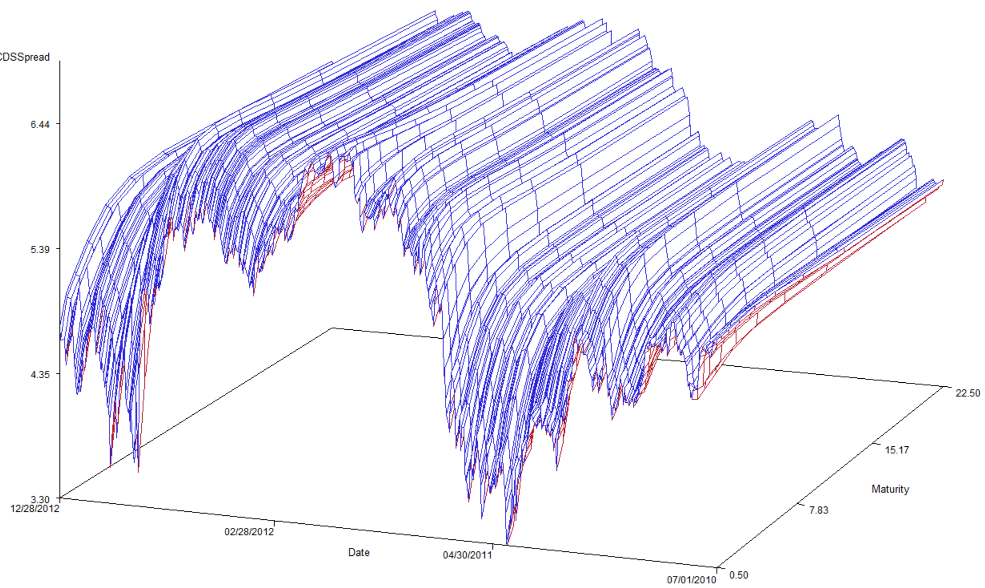


Figure 11
CDS Spread and Margins for the Cross-Section of Italian Bonds.

This figure shows time-series of the CDS spread for a 5-year contract and the margins applied to different maturity bonds by Cassa Compensazione e Garanzia.

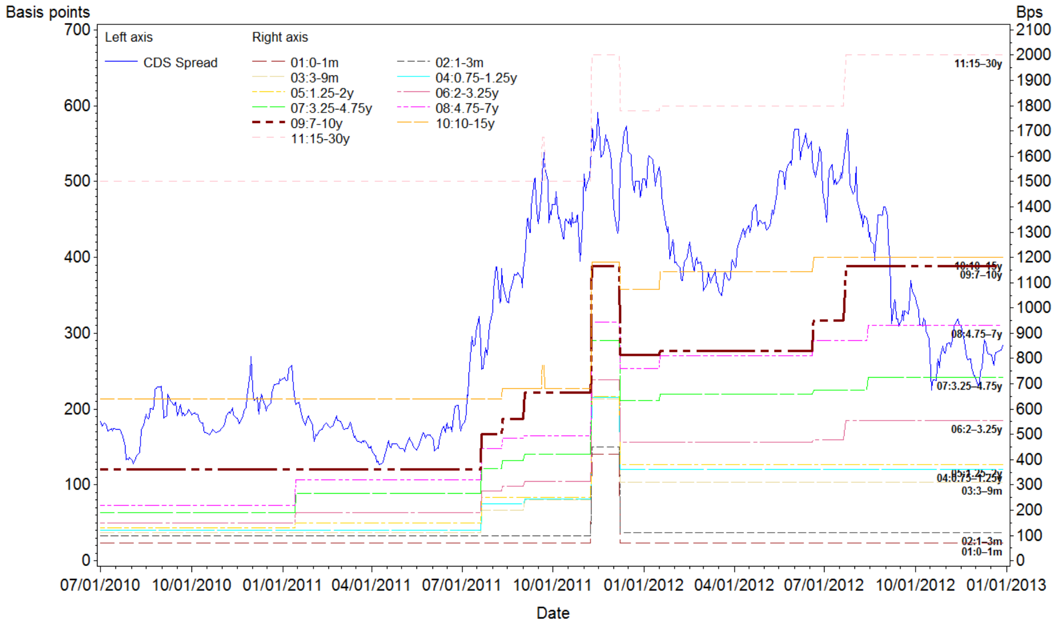
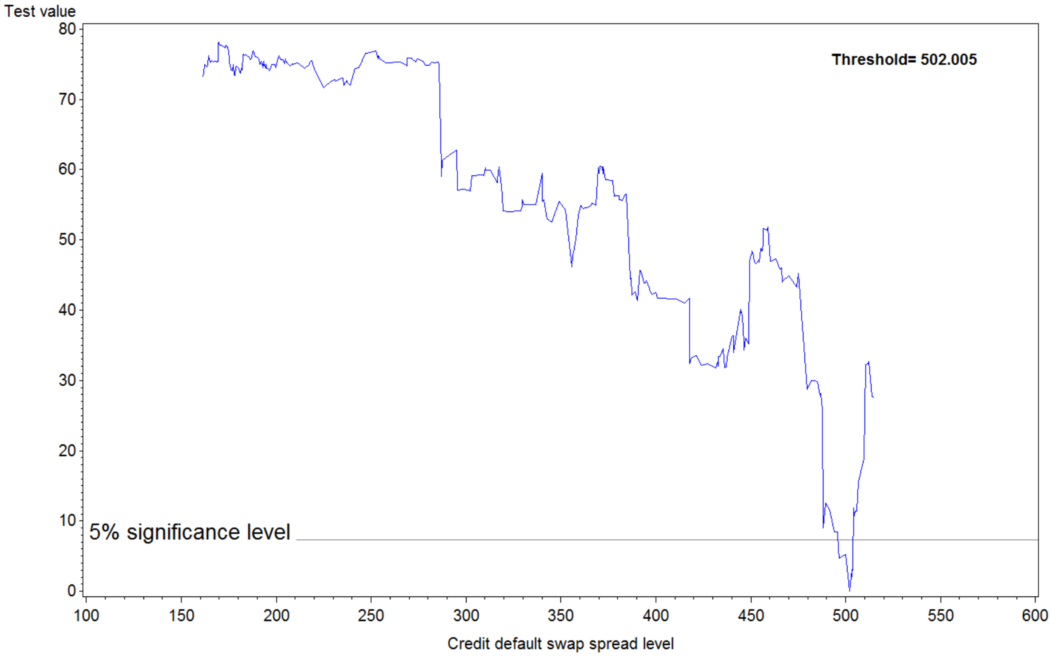


Figure 12
Confidence Bands Determination for the Panel Analysis.

The test statistic described in Appendix B is plotted here for Equation (8). The test statistic is normalized at 0 at the threshold that minimizes the sum of squared residuals. The horizontal line at 7.35 marks the 5% confidence values for the threshold.



Essay 2

Arbitraging Liquidity

Abstract:
This paper shows how arbitrage activity contributes to the convergence of liquidity across markets. Based on simple arbitrage arguments, I show how arbitrageurs' market and limit orders create co-movement across markets of bid prices, ask prices, and bid-ask spreads. Empirically, I document how the intensity of arbitrage activity increases the co-movement of market liquidity between securities linked by arbitrage. I test these hypotheses on Canadian stocks cross-listed in the United States, and then verify the generality of my results by repeating the analysis for the commonality across stocks and corporate bonds linked by capital structure arbitrage.

I Introduction

The concept of commonality in liquidity, i.e., the co-movement in market liquidity of different securities, was simultaneously introduced by Chordia, Roll, and Subrahmanyam (2000), Hasbrouck and Seppi (2001), and Huberman and Halka (2001), and has since been shown to hold both within and across markets. While the previous literature suggests that liquidity may co-move in different markets because of contemporaneous funding shocks, the particular trading mechanisms directly linking liquidities across markets, e.g., between securities traded in several markets, have mostly gone unexplored.

In this paper, I argue that the level of arbitrage activity, defined by profiting from divergences

I am thankful to my advisor, Lasse Heje Pedersen, my sponsor at NYU, Marti G. Subrahmanyam, and Loriana Pelizzon for their valuable comments. I also benefited from conversations with Yakov Amihud, Patrick Augustin, Jens Dick-Nielsen, Joel Hasbrouck, Søren Hvidkjær, Niklas Kohl, David Lando, Peter Norman Sørensen, Gyuri Venter, and participants to the seminar at the Stern School of Business at NYU, the Cass Business School, the Darden Business School, the Board of the Federal Reserve, the Saïd Business School, the Warwick Business School, and the Copenhagen Business School. I thank Jens Dick-Nielsen for sharing the code to clean and process the TRACE dataset. Support from the Center for Financial Frictions (FRIC), under grant no. DNRF102 from the Danish National Research Foundation, and from the Volkswagen foundation is gratefully acknowledged.

of prices of identical securities across markets, contributes to the liquidity convergence between markets. By detailing the trading strategies available to an arbitrageur, I show in a simple trading framework how the market and limit orders submitted by arbitrageurs create co-movement across markets and lead to the convergence of bid prices, ask prices, and bid-ask spreads. I test this theoretical prediction empirically and show that the intensity of arbitrage activity contributes positively to the co-movement of market liquidity between securities linked by arbitrage. To do so, I employ high-frequency data for Canadian stocks cross-listed in the United States, to verify my hypotheses. Finally, I show the generality of my results by considering an alternative arbitrage trade, and showing that the liquidity commonality across stocks and corporate bonds is increasing in the amount of capital structure arbitrage activity.

My first contribution is to analyze the trading strategies of arbitrageurs and derive testable implications. I show that, while the strategies available to the arbitrageurs include the use of both market orders, through which they consume liquidity, and limit orders, whereby they provide liquidity, arbitrage trading creates co-movement between the markets' liquidity. If the quotes are crossed, by which I mean that the bid price of one market exceeds the ask price of another market for the same security, the arbitrageur submits market orders, consuming liquidity, to take advantage of the available risk-less profit arising from the mispricing. Her strategy implies the convergence between the ask (bid) price of one market and the ask (bid) price of the other market. Furthermore, her strategies increase the bid-ask spreads in both markets. While crossed quotes correspond to the textbook case of arbitrage, when the arbitrageur can take advantage of the mispricing with certainty, the arbitrageur can also profit from trading in the two markets even when quotes do not cross. When quotes overlap, i.e., when the ask price of a market falls between the bid and ask prices of the other, there is no immediate risk-less profit to be made with certainty. However, the arbitrageur can make a profit by posting a limit order to buy just above the lower bid and, if that order is hit, closing her position by hitting the higher bid, thus selling the security at a profit. This strategy leads to a positive, albeit uncertain, profit. Similarly, the arbitrageur could post a limit order to sell just below the higher ask. If the order is hit, she can close her position by buying the security at the lower ask, again realizing a positive, although uncertain, profit. As in the case of crossed quotes, the arbitrageur's strategies will imply the convergence of bid (ask) prices.

Regardless of whether the arbitrageur employs limit or market orders in a specific quote setting, her trading strategies create a convergence, i.e., a positive correlation, between the bid prices in the two markets. By the same token, the arbitrageur's strategies imply a convergence between the ask prices and, ultimately, the midquotes and returns in the two markets. The co-movement between the pairs of quotes, bids and asks, results in the co-movement between the bid-ask spreads, that is, a co-movement between the liquidity measures in the two markets.

My second contribution is to empirically test this prediction that arbitrage activity increases the correlation between the liquidity in different markets. I do so by employing data on the quotes of 125 Canadian stocks that are cross-listed in the United States. During each of the six million plus trading seconds of 2013, for each of the 125 stocks, I establish whether an arbitrage opportunity was available between the stock listed in the United States and its counterpart traded in Canada, taking into account foreign exchange costs. I find that arbitrage opportunities are present in the markets 1.3% of the time, corresponding to about five trading minutes in each trading day.

I interpret the presence of large untapped arbitrage opportunities as lack of arbitrage activity. I support this identification by showing that when arbitrage opportunities are frequent, funding liquidity is scarce and the activity of high-frequency traders—the group of traders most likely to take advantage of fleeting profitable opportunities—is low. Furthermore, I support this identification by exploiting a rule in Regulation SHO, the extant legislation on short selling in the United States, which helps me identify short trades that are aimed at taking advantage of mispricing between a security traded in the United States and a security traded abroad, corresponding to the arbitrage I investigate. I show that these trades mostly occur when arbitrage opportunities arise, characterized by the price of the stock in the US exceeding that of the stock in Canada, i.e., when arbitrageurs would need to short the stock in the US.

I demonstrate the large degree of commonality in liquidity between securities linked by arbitrage between the Toronto and New York markets. The average intra-daily correlation, based on 30-minute intervals, between changes in the bid-ask spread for cross-listed securities is 47%, which is much larger than the degree of commonality reported in the literature for an individual stock and the rest of the market (Chordia et al., 2000), and for stocks sharing the same market maker (Coughenour and Saad, 2004).

As a first test of the relationship between arbitrage activity and liquidity commonality, I split my sample between stock-days with multiple arbitrage opportunities and those with few arbitrage opportunities, and show that the correlation between liquidity changes for securities connected by arbitrage is much larger for the sub-sample with few arbitrage opportunities, i.e., those with high arbitrage activity. For example, the correlation in liquidity changes over a one-minute interval is 7% for stock-days with a large number of arbitrage opportunities, and 25% for observations with a small number of arbitrage opportunities.

I seek to establish that the arbitrage channel is significant in determining the commonality between securities, even after controlling for alternative explanations. Drawing from existing models and previous empirical work on commonality in liquidity, I identify other channels that would cause the liquidity of cross-listed stocks to co-move. In a multivariate regression setting, I regress the commonality in the liquidity measure on the metric of arbitrage activity and other proxies identifying alternative channels, to verify that the arbitrage channel does not weaken when other factors are taken into consideration. On the contrary, the effect of arbitrage trading on commonality in liquidity is still highly statistically significant and economically meaningful.

My third contribution is extending the previous finding outside the realm of stock markets alone. The strategies I consider in the simple trading framework are only applicable to limit-order markets, which make up the vast majority of equity markets. Arbitrageurs aiming at taking advantage of mispricing between, for example, derivatives, would also trade in over-the-counter quote-driven markets. The arbitrageur would trade against market makers and consume liquidity from the markets. This strategy would also increase cross-market commonality in liquidity. I test this additional hypothesis that arbitrage activity increases liquidity spillover for a different arbitrage trade, using capital structure arbitrage, i.e., a trade that involves bonds and shares issued by the same company. I show that the commonality in liquidity between the bond and the stock market is higher when arbitrageurs are active, which supports the generality of my findings.

The result that arbitrage trading fosters commonality in liquidity is of interest to market participants who engage in trading of securities that are listed across different venues or securities that are linked to others by an arbitrage relation. Traders who profit from superior knowledge of the order flow, e.g., high-frequency traders, would also benefit from an understanding of the drivers of liquidity spillover between securities. Policy makers who design and supervise trading venues to be more or less integrated should take into account the impact of arbitrage trading on liquidity and its volatility. Finally, central banks, especially when considering open market and non-conventional policies, should be aware of the potentially detrimental effect that their operations of asset repurchases could have on markets that they are not targeting directly, because of arbitrage trading (Pelizzon, Subrahmanyam, Tomio, and Uno, 2014).

The paper is structured as follows: Section II reviews the existing literature, Section III develops testable hypotheses, formalized in a simple trading model, Section IV describes the data and measures I employ. The main empirical results in the paper are presented in Section V and tested for robustness in Section VI. Section VII extends my findings to another arbitrage mechanism and elaborates on the generality of my results and Section VIII concludes.

II Related Literature

This paper contributes to the existing literature by identifying the effect of arbitrageurs' activity on the commonality in liquidity between assets linked by an arbitrage relationship. As such, this paper adds to two strands of literature, the first addressing commonality in liquidity and the second identifying the effect that arbitrage trading has on liquidity.

The concept of commonality in liquidity was first introduced by Chordia et al. (2000)—contemporaneously with Hasbrouck and Seppi (2001) and Huberman and Halka (2001)—who showed that the market liquidity of single stocks traded on the New York Stock Exchange (NYSE) tends to co-move with the overall liquidity of the market, even after controlling for stock-specific determinants of liquidity. While Chordia, Roll, and Subrahmanyam do not provide a theoretical context, they suggest that the co-movement in market makers' inventories is one of the drivers of liquidity commonality, that is, they suggest a supply-side explanation. Brunnermeier and Pedersen (2009) develop a theoretical model detailing the relationship between the funding liquidity faced by the market makers and their provision of liquidity, lending a theoretical basis to the intuition in Chordia et al. (2000). Coughenour and Saad (2004) test whether market makers withdraw liquidity from the market when faced with binding liquidity constraints, thus causing the liquidity of the stocks they make markets for to co-move, and found empirical support for that hypothesis. Hameed, Kang, and Viswanathan (2010) also contribute to the supply-side explanation connecting funding liquidity and market liquidity by showing that negative market returns are followed by large commonality in liquidity. Recently, Koch, Ruenzi, and Starks (2016) brought forward a demand-side explanation for the commonality in liquidity between shares traded on the US stock market, showing that stocks that are owned to a larger extent by mutual funds share a common liquidity factor, attributing the commonality to the portfolio rebalancing dynamics of institutional investors. [1] The literature addressing the liquidity commonality of assets across (rather than within) markets is much sparser and generally does not identify the channels driving the commonality. An exception is Chordia, Sarkar, and Subrahmanyam (2005), who show that mutual fund flows negatively affect the commonality between the stock and the Treasury bond market, when funds rebalance their portfolios.[2]

I contribute to the commonality in liquidity literature by, first of all, focussing on the co-movement of liquidity *across* different markets, rather than *within* the same market. Second, I focus on the relationship between single assets connected by arbitrage, rather than on aggregate market quantities. I do this in order to pinpoint a clear channel of liquidity spillover between markets, i.e., I single out arbitrageurs as a group of traders contributing to the commonality in liquidity, via their cross-market trading.

The second strand of the literature that this paper contributes to is the one investigating the effect that arbitrageurs have on market liquidity. From a theoretical standpoint, there were early attempts to determine the arbitrageurs' effect on liquidity. In Kumar and Seppi (1994), arbitrageurs are modelled as faster traders, who have an advantage over other market participants in that they observe prices slightly before. In their model, arbitrageurs, who submit market orders, can add to or consume market liquidity, depending on the degree of their informational advantage. Holden (1995) shows, instead, that an increase in arbitrage activity leads to larger market liquidity, since

[1]Other noteworthy contributions to the literature on commonality in liquidity include Karolyi, Lee, and Van Dijk (2012), who investigate the validity of demand- and supply-side explanations in equity markets around the world, Kamara, Lou, and Sadka (2008), who demonstrate that the cross-sectional variation in commonality in liquidity increased due to patterns in institutional ownership, and Corwin and Lipson (2011), who show that commonality in liquidity in NYSE-traded stocks is mostly driven by program and other institutional traders. Papers that study commonality in liquidity in markets other than the equity market are Mancini, Ranaldo, and Wrampelmeyer (2013) and Karnaukh, Ranaldo, and Söderlind (2015) for the FX market (finding strong support for the funding liquidity channel), Mayordomo, Rodriguez-Moreno, and Peña (2014) for the corporate CDS market, and Cao and Wei (2010) for the option market.

[2]Pu (2009) shows that aggregate liquidity measures for the corporate bond and CDS market are correlated. Lee, Chien, and Liao (2012) perform a similar exercise for the Taiwanese stock index and its futures contract. Crotty (2013) shows related aggregate results for the corporate bond and equity markets. Zhang, Cai, and Cheung (2009), Brockman, Chung, and Pérignon (2009), and Bongaerts, Roll, Rösch, Van Dijk, and Yuferova (2015) show that the aggregate market liquidity of stock markets co-move with the liquidity of other, foreign, markets.

arbitrageurs compete with traditional market makers in liquidity supply, describing arbitrageurs as cross-sectional market makers, since they provide liquidity to traders in different markets at the same time. More recently, Foucault, Kozhan, and Tham (2017) bridge the two opposing views and show that when arbitrage is informationally motivated, arbitrageurs absorb liquidity from the market, and when arbitrage is liquidity-shock motivated, arbitrageurs provide market liquidity, instead. In their model, however, one of the markets has a null bid-ask spread in equilibrium, therefore does not provide testable predictions on the effect of arbitrageurs on liquidity commonality.[3]

From an empirical standpoint, the literature has first focussed on how liquidity affects the mispricing between assets. Roll, Schwartz, and Subrahmanyam (2007) show that arbitrage opportunities are larger when the equity market liquidity is lower, focussing on the index futures-cash arbitrage. Similar evidence is provided for the mispricing between corporate CDS and underlying bonds by Nashikkar, Subrahmanyam, and Mahanti (2011), and for the mispricing between American depository receipts (ADRs) and the underlying stocks by Chan, Hong, and Subrahmanyam (2008) and Gagnon and Karolyi (2010). Later, studies have focussed on reversing the research question, determining whether arbitrageurs provide liquidity to the market. Rösch (2014) shows, in the context of the ADR market, that arbitrageurs provide liquidity overall, since most mispricing follows demand shocks. Foucault, Kozhan, and Tham (2017) identify arbitrage opportunities arising from information- and liquidity-shocks and show that arbitrageurs provide liquidity following mispricing originating from demand shocks and diminish liquidity when the mispricing originating from differences in information across markets. Foucault et al. (2017) also show that an increase in technological advances employed by the arbitrageur is detrimental to liquidity. A similar point is made by Budish, Cramton, and Shim (2015), with a focus on the competition between arbitrageurs. Finally, Chaboud, Chiquoine, Hjalmarsson, and Vega (2014) show that a rise in algorithmic trading in the foreign exchange (FX) market resulted in fewer arbitrage opportunities and scarcer market liquidity.[4]

The only model with an explicit prediction on the relationship between arbitrage activity and commonality in liquidity is Cespa and Foucault (2014). They develop a model where two securities with correlated payoffs are traded by two dealers, separately, in two venues. The market makers learn about the value of the asset they make a market for from the other market. In this model, liquidity is tantamount to the precision of the signal the market makers observe. As arbitrageurs are assumed to provide liquidity, greater arbitrage activity means a higher liquidity and, therefore, a more precise pricing signal. This model predicts that, as arbitrage activity increases, the learning

[3]Multi-market trading models such as Subrahmanyam (1991), Chowdhry and Nanda (1991), and, more recently, Baruch, Andrew, and Lemmon (2007) and Lescourret and Moinas (2015) do not explicitly model arbitrageurs.

[4]I also contribute to the empirical literature on liquidity and price discovery for cross-listed securities. Previous studied using cross-listed securities data addressed the distribution of trading between markets (Sabherwal, 2007; Menkveld, 2008; Halling, Pagano, Randl, and Zechner, 2008; Halling, Moulton, and Panayides, 2013), the time-series determinants of market liquidity (Foerster and Karolyi, 1998; Silva and Chávez, 2008; Zhang, Cai, and Cheung, 2009; Moulton and Wei, 2009; Dang, Moshirian, Wee, and Zhang, 2015), and the contribution of each market to price discovery (Eun and Sabherwal, 2003; Menkveld, Koopman, and Lucas, 2012).

is more precise and, therefore, the liquidity of the markets co-move to a smaller extent. While this model assumes that arbitrageurs provide liquidity, it implies that greater arbitrage activity results in a weaker commonality in liquidity, which is a different prediction than the one I arrive at by considering the arbitrageurs' trading strategies in the next section.

I contribute to the understanding of the relationship between arbitrage activity and market liquidity by developing a simple trading model detailing the arbitrageurs' strategies and deriving the implication that market liquidity measures are more correlated when arbitrageurs are active on the market. I test this implication empirically and show that, when there are fewer arbitrage opportunities, which I interpret as a higher share of arbitrageurs' activity, the market liquidities of assets connected by arbitrage tend to co-move more.

III Hypotheses Development

Arbitrageurs profit from having exclusive or preferential access to different markets, which allows them to take advantage of cross-market mispricing. They stand ready to trade in different, connected markets, acting as what Holden (1995) calls cross-sectional market makers. Traditional market makers, on the other hand, focus on providing liquidity on a single market, standing ready to trade with liquidity demanders, profiting from their asynchronous arrival.[5] I aim to understand how the activity of cross-market arbitrageurs affects the commonality between the liquidity of assets linked by arbitrage. To do this, I analyze, in Subsection III.A, the trading strategies available to the arbitrageurs and derive empirical predictions. Subsection III.B lays out alternative hypotheses explaining the linkages between the liquidity of securities connected by arbitrage.

III.A Arbitrageurs' Activity

I focus on the trading strategies available to arbitrageurs, once they enter a market with exogenously given bid- and ask-prices. I then derive implications on the co-movement of liquidity, given the arbitrageurs' trading behavior. The classic characterization of arbitrageurs trading as buying and selling mispriced securities suggests that arbitrageurs will only trade via market orders, hitting existing limit orders and subtracting liquidity from the market. Chaboud et al. (2014) show that, on the FX market, algorithmic traders increase informational efficiency, reducing arbitrage opportunities, while *providing* liquidity, suggesting that arbitrageurs can profit from strategies that include liquidity provision. In light of these findings, in order to understand the effect that arbitrage trading has on liquidity co-movement, one cannot assume that arbitrageurs only trade with market

[5]Differentiating between arbitrageurs and market makers based on their access to the markets is common in the literature. Goldstein, Li, and Yang (2014) model arbitrageurs as traders having access to a larger set of assets, as compared to mutual funds and individuals, whose investment opportunity set is small. Similarly, in Foucault et al. (2017), market makers are specialized in a single security while arbitrageurs trade across securities.

orders, but should instead consider all possible strategies available to them, including those that improve market liquidity.

I derive the strategies available to the arbitrageurs in the context of typical order-driven equity markets, with price-time priority order books, such as the New York Stock Exchange, the NASDAQ, and the Toronto Stock Exchange, i.e., the markets that are object of most of the empirical work in this study. Figure 1 exemplifies the scenarios arbitrageurs face when trying to profit from the mispricing between two securities, security 1 and security 2, linked by arbitrage and traded on markets 1 and 2. A_1 and A_2 stand for the ask prices, B_1 and B_2 stand for the bid prices in markets 1 and 2, respectively.

Insert Figure 1 here.

Panel A of Figure 1 provides an instance of crossed quotes. This setting represent the textbook example of arbitrage, since the arbitrageur can contemporaneously hit the order at the bid of market 2 and lift the order at the ask in market 1, purchasing the security for A_1 and selling it for B_2, thus locking in a risk-less profit of $B_2 - A_1 > 0$ dollars per unit traded. The arbitrageurs can repeat this trading strategy, causing the ask-price in market 1 to raise and the bid-price in market 2 to diminish, as long as B_2 is larger than A_1. This strategy demands liquidity from both markets, and widens the bid-ask spreads in market 1 and 2.

Alternatively, to exploit the mispricing and her dominant role as cross-market trader, the arbitrageur could post a limit order to sell at A_2 or lower (to exploit price priority) and a limit order to buy at B_1 or higher. In case one of the limit orders was to be hit, the arbitrageur could then close her position instantaneously by trading, at a profit, on the other market. For example, if her limit order to buy just above B_1 on market 1 was hit, she could close her position by hitting the bid in market 2, hence selling the security for $B_2 > B_1$. As the first strategy leads to a risk-less, instantaneous, and certain profit, I expect the arbitrageur to first take advantage of the mispricing between B_2 and A_1, thus turning the markets from displaying crossed quotes to overlapping quotes, as shown in Panel B.

In Panel B, no arbitrage opportunity is readily available to be profited on, since the bid- and ask-prices of the two markets do not cross. However, the arbitrageur is still able to profit from the privileged position she holds, i.e., being able to trade in both markets. The arbitrageur can offer to acquire the security on market 1 by posting a limit order to buy above B_1. If the limit order to buy is hit, she acquires the security on market 1, and she can close her position by selling that same security at B_2 on market 2. She can repeat the strategy for as long as B_1 and B_2 differ. Similarly, she can post a limit order to sell at A_2 or lower and, when that is hit, close her position by buying the security for A_1 on market 1. She can repeat this strategy as long as A_1 and A_2 differ.

Finally, Panel C shows a case of included quotes, where the bid- and ask-prices of one market are included within the bid- and ask-prices of the other. In this situation, the arbitrageur can still profit from her position as a cross-market trader by posting a limit order to sell at A_1 or lower (buy at B_1 or higher) and, if it is hit, close her position by lifting the order at A_2 (B_2).

In all the cases discussed above, the trading strategies of the arbitrageur imply the convergence of the ask-prices, i.e., the convergence of A_1 to A_2, and the convergence of the bid-prices, i.e., the convergence of B_1 to B_2. The expectation held in the existing literature that arbitrageurs make prices converge across markets, where each market is represented by a single price, carries through when considering a more realistic setting, where each market features a price to sell and a price to buy: Arbitrageurs make bid-(ask-) prices converge. As the bid and ask sides of market 1 and 2 converge when the arbitrageur is trading, it follows that so does the bid-ask spread. As arbitrageurs are active on the market, the bid-ask spreads between markets converge.

Given the trading strategies and the intuition above, I formalize the effect that arbitrageurs' trading has on the correlation in bid-ask spreads, i.e., the commonality in liquidity between markets, by developing a simple framework of arbitrageurs' trading behavior. Let us assume that a security with underlying value α is traded in two order-driven markets. In both markets, the tick size equals 1 cent. The bid-price in market 1 is $B_1 = \alpha + \varepsilon_1$ where ε_1 takes the value of -0.01, 0, or 0.01 with equal probability $\frac{1}{3}$. The ask-price is given by $A_1 = B_1 + \mu_1$ where μ_1 is equal to 0.01 or 0.02, with equal probability $\frac{1}{2}$. Similarly $B_2 = \alpha + \varepsilon_2$ and $A_2 = B_2 + \mu_2$ where ε_2 and μ_2 are independent and identically distributed to ε_1 and μ_1, respectively. In this framework, the bid-ask spreads quoted on the two markets are ex-ante uncorrelated, since ε_1, μ_1, ε_2, and μ_2 are uncorrelated. While this feature is certainly a simplification, I only aim to determine the marginal effect of including arbitrage trades to a setting without arbitrageurs. I assume that the order book consists of one share available at each price level at and below the bid-price and at and above the ask-price. I do this to focus on a single dimension of liquidity, summarized by the bid-ask spread, i.e., a round-trip cost measure.

The time-line of the events I am considering is as follows. The arbitrageur arrives on the market and observes A_1, B_1, A_2, and B_2. The arbitrageur can submit market orders, hence executing trades at the existing prices. Alternatively, she can submit limit orders above the bid- or below the ask-prices, to take advantage of price priority. After the arbitrageur's submission, a trader enters the market, submits a market order and trades at one of the four available prices, with equal probability. Finally, the arbitrageur can submit a last market order to close her position. After that, the arbitrageur cancels her remaining orders, if any, the quotes change and the game starts from the beginning, with a new set of quotes.

As a means of comparison, consider a similar setting without the presence of the arbitrageur. Before the advent of the trader and her trade, the bid-ask spreads in the two markets are uncorrelated, by construction. When the trade takes place, one of the bid- or ask-sides is hit and moves either closer or further away from its counterpart on the other market. While the correlation between quotes is null, one of the two bid-ask spreads widens, while the other remains unchanged, thus causing the liquidity measure to be negatively correlated across markets.

When the arbitrageur is present, however, both quotes and liquidity measures are more positively correlated. First of all, let us consider the liquidity in the markets prior to the advent of the trader but following the arbitrageur's orders submission. Consider the case in Panel A of Figure 1.[6] In the case of crossed quotes, the arbitrageur subtracts liquidity from both markets, diminishing the higher bid and increasing the lower ask. Her trades widen both bid-ask spreads, and contribute to their positive correlation.

When the quotes are overlapping (as in Panel B of Figure 1) or included (as in Panel C of Figure 1), the arbitrageur's strategy includes providing liquidity to the market that has the least of it: In this setting, the arbitrageur has to better the prices to obtain execution of her limit orders, as she only submits limit orders in the market(s) where $\mu = 0.02$, hence bettering that market's liquidity. If both markets have a wide bid-ask spread ($\mu = 0.02$), she will provide liquidity to both, reducing the bid-ask spreads. If only one of the markets has a wide bid-ask spread, the arbitrageur will provide liquidity to that market alone. The arbitrageur's actions thus contribute to the positive correlation between bid-ask spreads, by submitting limit orders and tightening the bid-ask spread on the market that has the largest one. It follows that, before the advent of the trader, the bid-ask spreads of the two markets are positively correlated, in the presence of the arbitrageur. Alternatively, considering liquidity separately for each side, the arbitrageur's strategy implies raising the lower bid, thus providing liquidity to the market where a seller would have found a worse liquidity, and lowering the higher ask, hence providing liquidity to the market where a buyer would have found a worse liquidity. None of the arbitrageur's strategies, when she provides liquidity, includes providing liquidity by raising the higher bid or lowering the lower ask.

After the trader's arrival, the execution of her market order subtracts liquidity from one market, while holding the other market's liquidity unchanged, thus contributing negatively to the commonality between bid-ask spreads. If the quotes were crossed to start with, the arbitrageur would have no influence on the liquidity in the markets after the trader's trade. If the quotes were overlapping or included, however, the presence of the arbitrageur's order can dampen the effect of the trader's market order: If the trader's order hits the arbitrageur's standing limit order, the trader subtracts liquidity from, e.g., market 1. The arbitrageur, subsequently, closes her position by hitting an order in market 2, hence lowering the liquidity of market 2, contributing positively to the co-movement of the markets' liquidities. Finally, if the trader's order does not hit the arbitrageur's order and the arbitrageur cancels her orders, and all but one of the final quotes revert to their original positions, i.e., the state before the actions of the arbitrageur. It follows that the overall effect of the presence of the arbitrageur, both before and after the trader's arrival, contributes positively to the commonality in liquidity between the two markets.

I formalize my findings in the following proposition:

Proposition 1 *Consider two securities linked by arbitrage. When arbitrageurs are present on the*

[6] I assume that the arbitrageur prefers locking in a sure profit first, without the use of limit orders. Relaxing this assumption and assuming the arbitrageur would post limit orders does not affect the results.

market:

1) *The bid prices of the two markets are more positively correlated than in the arbitrageurs' absence. The same is true for ask prices, midquotes, and returns.*
2) *The bid-ask spreads of the two securities co-move more than in the arbitrageurs' absence.*

Calculations can be found in the Appendix. The predictions are robust to allowing multiple trades from exogenous traders to take place, and allowing trades to be correlated across markets, i.e., allowing trades to take place at both bids or both asks at the same time, as it would be the case it traders split their orders across markets. Trading volume, another possible liquidity measure, can also be trivially shown to co-move more in the presence of an arbitrageur.

To summarize, based on a simple framework of the arbitrageur's trading behavior, I expect the liquidities of the markets for securities traded on different exchanges and connected by arbitrage to co-move more when arbitrageurs are present on the market.

III.B Alternative Hypotheses

While this paper sets out to test the proposition that arbitrageurs' activity increases liquidity commonality between securities connected by arbitrage, an alternative hypothesis can be surmised, from the existing literature, as to what other factors can drive the commonality. To stay in line with the literature, I lay out alternative factors, separating them between supply- and demand-driven.

Arbitrageurs can be classified as supply-side players who cause the liquidity of markets connected by arbitrage to co-move. Other supply-side actors are, for example, market makers, who also contribute to the commonality in liquidity. Coughenour and Saad (2004) find that the liquidity of stocks that share market makers tend to co-move. I have no available measure or confirmation of the involvement of market makers across foreign markets. However, Menkveld (2013) characterizes the trading of a high-frequency trader (HFT) involved in two markets, describing it as a new type of market maker. As a similar market maker could be envisioned to be trading between the US and the Canadian market, I expect that greater across-market market-making activity results in a larger amount of commonality.[7]

Since some traders are indifferent to where they trade, I expect traditional (single market) market makers to play a role in the cross-market commonality in liquidity in their effort to attract traders from the other market. That is, I expect market makers to be more likely to match quotes in a competing market, hence fostering commonality in liquidity, the closer substitutes the markets are to the traders, i.e., the more indifferent the traders are to trade on one market rather than the other, such as in the market for an underlying asset and its derivative.

I lay out a third and last supply-side explanation. Following Brunnermeier and Pedersen (2009), I expect that, since market makers in different markets are likely to be exposed to similar

[7] In the following, HFT is used as a short hand for both high frequency traders and high frequency trading.

funding liquidity shocks, a global decrease in finding liquidity result in a global decrease in market liquidity. Similarly, as put forward by Hameed et al. (2010), as the stock market declines, market makers in different stocks are faced with similar binding constraints. I expect the co-movement of liquidity of cross-listed securities to be larger during market downturns and in period of market turmoil.

As far as demand-side explanations are concerned, Koch et al. (2016) show that stocks with a larger share of mutual fund ownership tend to co-move more with each other, which they attribute to the liquidity provision during the rebalancing of mutual fund portfolios. The same argument could be especially made for the commonality between the liquidity of securities linked by arbitrage, i.e., the liquidity of cross-listed securities could move more tightly when mutual funds own a larger share of the stock. Specifically, since mutual funds are relatively sophisticated traders, I expect them to be more concerned with the liquidity of the security, and less so where the security is traded. Therefore, when rebalancing their portfolio, mutual funds will purchase or sell the securities across all the markets the security is traded in, thus fostering liquidity co-movement.

While mutual funds are among the larger players in the market for whom I can observe ownership, I cannot similarly observe the holdings of other actors and their portfolio rebalancing actions. I can assume, however, that at least some investors might rebalance their position in a stock using either or both markets, for example, after news relevant to the company's fundamentals are disclosed. Therefore, I expect commonality in the liquidity offered in the market to be correlated with and partially explained by commonality in trading activity.

IV The Data

My analysis focuses on 125 Canadian companies that have stocks listed on both the Toronto Stock Exchange, Canada's largest stock market, and a stock market of the United States, either the NASDAQ or the NYSE), over 243 full trading days in 2013. The Appendix lists the cross-listed companies, their tickers in the US and Canada, their sector, and market capitalization as of December 2013. Almost half of the companies belong to the mining, quarrying, oil and gas industry and their median market capitalization is 1.4 billion US dollars, corresponding to about the 35th percentile of the US stock market for that period. The companies in this study are, thus, smaller and more specialized than the typical US stock market sample. I require the companies to be cross-listed throughout 2013 and to trade at least 20 days a year.[8]

[8]While Canadian companies list their shares on either the New York Stock Exchange or the NASDAQ at first, they trade on both markets. I require the trading days to be ordinary, hence I discard holidays and the days before them, when the markets operate on a reduced schedule. I require both the American and Canadian market to be open, which is generally the case. To avoid the concern that beginning- and end-of-day operations and auctions affect the estimates, I only retain observations that took place after 9.35 AM and before 3.55 PM. Of the 172 companies recorded as cross-listed in the Toronto Stock Exchange, I discard 47: five because the shares were quoted in US Dollars (USD) on the Canadian exchange or were exchange traded funds; six because they were delisted during 2013, 28 because

I obtain second-stamped quotes and trades from the Toronto Stock Exchange (TSE), for the prices on the Canadian counterpart of the securities. The dataset includes all updates of the best bid and ask prices and quoted quantities for all securities traded on the TSE. I compile a similar dataset for the US counterparts of these securities using the Trades and Quotes (TAQ) dataset. I employ trade data for both markets and I sign them following the Lee and Ready (1991) algorithm.

To calculate the presence of arbitrage opportunities as they appeared on the market, I need to determine the applicable exchange rate at the time.[9] Therefore, I obtained microsecond-stamped foreign exchange (FX) rates for the USD/CAD pair from Reuters. The dataset reports firm, executable bid- and ask-side FX rate quotes, allowing me to take the liquidity of the foreign exchange market into account. Previous analysis of the mispricing of ADRs and ordinary Canadian did not characterize arbitrage opportunities at the level of detail that I aim to achieve, due to the lack of availability of high-frequency FX data. Although the FX market has been regarded as one of the most liquids markets, Mancini et al. (2013) and Chaboud et al. (2014) have shown that traders can experience significant transaction costs. My dataset is obtained from Thomson Reuters—which maintains the largest market share for Commonwealth-based pairs—and allows me to include the cost incurred in the FX market in the arbitrage opportunity calculations.[10]

I obtain details on the companies from the Center for Research in Security Prices (CRSP), shorting activity from the NASDAQ, mutual fund holdings are obtained from the CDA/Spectrum database from the Wharton Research Data Services (WRDS), and funding liquidity measures from Bloomberg. Moreover, I use message-level data obtained from NASDAQ, detailing every message received by the exchange, to calculate the activity level of high-frequency traders.

IV.A Arbitrage Measures

To evaluate the effect of the arbitrageurs' presence on the market, it would be ideal to have access to a direct measure of their activity. Unfortunately, to my knowledge, such a measure has not been presented to any academic study to date. However, a metric used in previous works (Foucault et al., 2017; Rösch, 2014) to calculate arbitrageurs' activity—or lack thereof—is the presence of arbitrage opportunities, which is the approach I take here. In Subsection V.A, I show evidence that my measure actually captures arbitrageurs' activity rather than fortuitous mispricings.

they had a minimum trading price below 1 CA Dollar (CAD), resulting in sub-penny quoting; and 8 because they traded less than 20 days in 2013. All variables are winsorized at the 2.5% level. Observations for the stock of Telus Corporation are dropped for the month of January since the company went through a conversion of non-voting shares into common shares, altering the normal trading for the shares and the cross-listed counterparts.

[9]This is to examine arbitrage in the stricter sense, i.e., by settling all trades instantaneously, rather than waiting for netting.

[10]Thomson Reuters' closest competitor is Electronic Broking Services, which dominates the market for all other pairs (Chaboud et al., 2014). In the Appendix I compare the FX data from Thomson Reuters to the aggregate feed obtained from Olsen data, a company that consolidates the quotes of multiple FX dealers. I find that Thomson Reuters generally quotes a wider spread than the market as a whole. The bias resulting from employing Thomson Reuters, thus, would be to underestimate the presence of arbitrage opportunities, as Arb_{its} is decreasing in the bid-ask spread.

In order to correctly identify actual trading opportunities, I need to match bid and ask prices on the three markets that would be involved in an arbitrage transaction: the TSE, the US stock market, and the FX market. I do so at a one-second frequency, calculating, at the end of each second, the best bid and ask on the US stock market, using TAQ data, the corresponding quotes on the Canadian market, using prices prevailing on the TSE, and the best bid and ask quotes for an FX transaction.

I define the arbitrage opportunity for stock pair i, on day t, at second s as

$$AO_{its} = \max\left[\frac{Bid_{CA}}{Ask_{FX}} - Ask_{US}, Bid_{US} - \frac{Ask_{CA}}{Bid_{FX}}, 0\right] \tag{1}$$

where Bid_{US}, Ask_{US}, Bid_{CA}, Ask_{CA}, Bid_{FX}, and Ask_{FX} are defined intuitively and the FX rate is expressed as CA per US dollar. The first term in the max operator corresponds to the strategy of selling a share in Canada by hitting the standing bid-price and covering the position by lifting a share in the US at the ask-price, while the second term corresponds to the opposite strategy. The 0 term constrains the arbitrage trade to have a non-negative profit.[11]

For example, on January 2, 2013, at 3:40:53 PM, Toronto Dominion was quoted at a bid and ask of USD 84.47 and 84.48, respectively, in the US, and at a bid and ask of CAD 83.26 and 83.27, respectively, in Canada. Contemporaneously, 1 US dollar could buy 0.9854 CA dollars (Bid_{FX}) and 0.9855 CA dollars could buy 1 US dollar (Ask_{FX}). The arbitrage opportunity was, therefore, $\max\left[\frac{83.26}{0.9855} - 84.48, 84.47 - \frac{83.27}{0.9854}, 0\right] = \max[0.005, -0.034, 0] = 0.005$, i.e., the arbitrageur could have locked in a riskless profit of half a cent by selling the stock in Canada for CAD 83.26, buying USD $\frac{83.26}{0.9855} = 84.485$ with the sale proceeds, and covering her position by buying the stock in the US for USD 84.48. Figure 2 shows the arbitrage opportunities for Toronto Dominion on January 2, 2013, between 3:40:00 PM and 3:40:59. Panel A shows the arbitrage opportunities shaded in grey, calculated as per Equation 1. To highlight the importance of taking the FX liquidity cost into consideration, Panel B shows the arbitrage opportunities calculated as per Equation 1, but where corresponding FX midquote is employed instead of Bid_{FX} and Ask_{FX}. Clearly, the liquidity of the FX is an important determinant of arbitrage profitability, and ignoring this aspect will lead to an overestimation of the frequency of arbitrage opportunities.

Insert Figure 2 here.

In the remainder of the paper, I focus on a daily measure of arbitrage opportunities, namely their frequency Arb_{it}:

$$Arb_{it} = \frac{1}{S}\sum_{1}^{S} I\left[AO_{its} > 0\right] \tag{2}$$

[11]The existence of make- and take-fees would require the arbitrage opportunity to be larger than the sum of the fees on the two markets. I account for this extra cost by repeating our analysis and only counting AO_{its} in Arb_{it} if it is larger than 0.006, which is a conservative estimate consistent with (twice) the fee structure reported in Foucault, Kadan, and Kandel (2013) and Malinova and Park (2015). The results are reported in the Appendix.

where AO_{its} was defined in Equation 1, S is the total amount of trading seconds on day t, and I is the indicator function. A daily observation of $Arb_{it} = 0.03$ should be interpreted as showing that arbitrage opportunities arose 3% of the time for stock i, on day t. Alternative arbitrage measures, which will be used to verify the robustness of the main results in the paper in Section VI, are defined as follow:

$$MaxRelArb_{it} = \max_s \left[\frac{AO_{its}}{\frac{1}{2}Bid_{US} + \frac{1}{2}Ask_{US}} \right] \qquad RelArb_{it} = \frac{1}{S}\sum_{1}^{S} \frac{AO_{its}}{\frac{1}{2}Bid_{US} + \frac{1}{2}Ask_{US}}$$

where $MaxRelArb_{it}$ measures the maximum return to an arbitrage opportunity for stock i on day t, $RelArb_{it}$ measures the size of the arbitrage opportunity relative to the capital required to take advantage of it, i.e., the price of the stock. Capturing a different dimension of the arbitrage opportunities, I calculate their average duration $Duration_{it}$. Finally, I obtain a more conservative estimate of Arb_{it}, requiring the arbitrage opportunity to yield at least a return of 1 basis point, $Arb1bp_{it} = \frac{1}{S}\sum_1^S I\left[AO_{its} > 0.0001\frac{Bid_{US}+Ask_{US}}{2}\right]$.

As a final alternative measure of arbitrageurs' activity, I calculate the half-life of a pricing shock, i.e., how long it takes for the co-integrated price system to absorb half of a 1\$ pricing shock. I define the half-life as $HalfLife_{it} = \frac{\log(0.5)}{\log(1+\alpha_{US}-\alpha_{CA})}$. In this definition, the αs are adjustment parameters to the $(1,-1)$ co-integrating vector in an error correction model estimated at a daily frequency using second-level midquotes P^{US}_{its}, $P^{CA,USD}_{its}$ (where the latter is measured in USD). The half-life measures how long it takes for the system to absorb half of the shock to either price. The average half-life in the sample is 49 seconds, meaning that, on average, following a USD 1 change in one of the prices, the difference in prices diminishes to USD 0.5 within 49 seconds.[12]

Panel A of Table I reports descriptive statistics for the arbitrage measures. The median cross-listed stocks pair is mispriced 1.3% of the time, corresponding to about 5 minutes a day. However the arbitrage opportunities are generally small, as only two minutes a day the arbitrage is larger than 1 basis point. In about 8% of stock-days, there are no arbitrage opportunities, while 50% of the stock-days feature mispricing between 0.3% and 3.4% of the time, corresponding to 1 and 13 minutes, of which only between 20 seconds and 8 minutes feature a sizeable arbitrage.

Insert Table I here.

For the median stock, the largest daily arbitrage opportunity is 5 bps, with an interquartile spread of 7.8 bps. The arbitrage opportunities are, in general, small, with 95% of the stock-days having a maximum arbitrage below 27 bps. The arbitrage opportunities are short-lived, with half

[12] I estimate

$$\begin{pmatrix}\Delta P^{US}_{its}\\ \Delta P^{US}_{its}\end{pmatrix} = \begin{pmatrix}\gamma^{US}_{it}\\ \gamma^{CA}_{it}\end{pmatrix} + \begin{pmatrix}\alpha^{US}_{it}\\ \alpha^{CA}_{it}\end{pmatrix}\left(P^{US}_{i,t,s-1} - P^{CA,USD}_{i,t,s-1}\right) + \epsilon_{its}$$

where $\alpha^{CA}_{it} > 0 > \alpha^{US}_{it}$. Allowing for short term dynamics has a negligible effect on $HalfLife_{it}$.

of them lasting less than 5 seconds. On the vast majority of days, the average arbitrage opportunity lasts less than one and a half minute.

IV.B Measures of Liquidity Commonality

In order to capture the co-movement between the liquidities of the cross-listed stocks in the two markets, I follow the existing literature (Chordia et al., 2000, Coughenour and Saad, 2004, Koch et al., 2016 and others) and obtain daily estimates of liquidity commonality by regressing log-changes in a liquidity measure for the stock traded in the U.S. market on log-changes for the corresponding liquidity measure prevailing in Canada. To obtain daily estimates, I perform the regression on half-hour intervals during the day.

Therefore, for a given liquidity measure L_{ith}^{US}, estimated for stock i on day t at the h-th half-hour interval on the US market, I estimate

$$\Delta \log L_{ith}^{US} = \alpha_{it} + \beta_{it} \Delta \log L_{ith}^{CA} + \epsilon_{ith} \tag{3}$$

and obtain the R-square $R^2_{L,it}$, with a larger R-square meaning more liquidity commonality.[13]

The liquidity measure I use in the remainder of the paper is the bid-ask spread, defined as the difference between the best bid- and ask-prices available in the markets. For purpose of robustness, I define also other liquidity measures, which I use to make sure that my results are general. I calculate the relative bid-ask spread, defined as the ratio between the quoted bid-ask spread and the prevailing midquote; the effective bid-ask spread, defined as twice the signed difference between the trade price and the midquote; the realized bid-ask spread, defined as twice the signed difference between the trading price and the midquote prevailing five minutes after the trade; the Amihud measure, defined as the ratio between the absolute return and the volume traded.

The liquidity measures are thus defined as follows, respectively:

$$BA_{itm} = Ask_{itm} - Bid_{itm} \qquad RelBA_{itm} = \frac{Ask_{itm} - Bid_{itm}}{0.5(Ask_{itm} + Bid_{itm})}$$

$$EffBA_{ite} = 2Q(e)(P_e - m_{ite}) \qquad ReaBA_{ite} = 2Q(e)(P_e - m_{it(e+5)})$$

$$Ami_{itm} = \frac{|r_{itm}|}{Vol_{itm}}$$

for each trading minute m and trade e. $Q(e)$ equals one if the trade is a buy and minus one if the trade is a sell, m_{ite} is the midquote prevailing at the time of trade e, $m_{it(e+5)}$ is the midquote prevailing five minutes after trade e, r_{itm} is the stock price return between the beginning and the

[13]Estimating Equation 3 with $\Delta \log L_{ith}^{CA}$ as regressand and $\Delta \log L_{ith}^{US}$ as regressor would lead to the same result, since the R-square corresponds to the squared correlation between right- and left-hand side variables. I employ differenced liquidity measures in Equation 3 to follow the literature; however, my liquidity variables do not have the statistical properties of unit roots.

end of minute m and Vol_{itm} is the volume traded during that same minute. All liquidity measures are aggregated at a half-hour frequency into the corresponding L^{CA}_{ith} and L^{US}_{ith} .

I report my main results using the quoted bid-ask spread as the liquidity measure and employ the other measures as robustness checks. I am wary of performing the analysis on the relative bid-ask spread $RelBA_{itm}$ and the Amihud measure Ami_{itm}, since I investigate the relationship between liquidity commonality and arbitrage opportunity. These two measures will tend to co-move to a larger extent when the arbitrage activity is more intense, since the prices in the US and Canada will move more tightly. The effect that arbitrage activity has on the correlation between the midquotes in the US and Canada, which feature in the denominator of $RelBA_{itm}$, and the returns in the US and Canada, which feature in the numerator for Ami_{itm}, mechanically affects the correlation between the liquidity measures in the two markets. I report them nonetheless, for robustness and completeness.

Panel B of Table I reports the descriptive statistics of the liquidity variables I employ. The liquidity of the two markets is remarkably similar, with the average bid-ask spreads being USD 0.026 and CAD 0.027 and the relative bid-ask spread being 0.003 and 0.004.[14] The Amihud measure is twice as large in Canada as in the US and I attribute this to the different coverage of my datasets, since the TAQ data covers every transaction taking place in the US, while the Canadian dataset covers only trades taking place on the Toronto Stock Exchange.

The liquidity commonality measures are reported in Panel C of Table I. The average (median) daily bid-ask spread commonality measured at a half-hour frequency is 30% (23%), with half of the observations ranging between 6% and 49%. These estimates imply a remarkable amount of liquidity commonality between securities connected by arbitrage. To gauge the sizeable amount of commonality implied by these estimates, I compare them to similar quantities present in the existing literature. Chordia et al. (2000) using daily data for a subset of New York Stock Exchange (NYSE) stocks with the average market liquidity at 1.7%. Coughenour and Saad (2004) report the commonality between a set of stocks and other stocks traded by the same market maker to be 25%, using intraday data and 3% when using daily data. The comparable figure for my study, estimating Equation 3 using daily $\Delta \log BA_{it}$, is more than eight times larger, amounting to 24%.

This comparison highlights the large extent of co-movement in liquidity between cross-listed stocks, the drivers of which are analyzed in the next section. While a large correlation in liquidity could be expected for stocks traded on different markets, either due to the stocks' intrinsic characteristic or to demand side drivers, such a relation, to my knowledge, has not been established in the existing literature.

[14] I express the absolute measures in CAD and USD for the Canadian and US market, respectively, to avoid attributing volatility in the FX rate to the liquidity measures. The conversion ratio between the stocks traded in Canada and the US is 1-to-1 and the FX rate is very close to unity, increasing from 0.99 to 1.07 CAD per USD during the year; thus, the absolute bid-ask spreads represents comparable quantities.

IV.C Other Variables

In Subsection III.B I highlighted other factors that would induce commonality in the liquidity of cross-listed securities. Here, I define the variables that I use to control for channels alternative to the effect of arbitrage trading.

To capture the intuition in Menkveld (2013) that high-frequency traders can behave like dealers across markets, I calculate the commonality in high-frequency trading estimating Equation 3 using a measure of HFT activity, namely the ratio of trades to messages as a measure of HFT, following Hendershott, Jones, and Menkveld (2011). I expect this measure of HFT commonality $R^2_{HFT,it}$ to positively affect the commonality in liquidity across markets: Menkveld (2013) finds that cross-market HFTs trade mostly by posting limit orders and, thus, providing liquidity to both markets at the same time. If the HFT was to stop trading, market liquidity would worsen in both markets, once again resulting in a larger commonality between markets.

To measure the degree of substitutability between the two markets and, thus, the degree of potential competition between market makers in the US and Canada, I calculate a scaled liquidity difference measure, based on the volume traded in the US and Canada, and defined as $VolDiff_{it} = \left|\frac{Vol^{US}_{it} - Vol^{CA}_{it}}{Vol^{US}_{it} + Vol^{CA}_{it}}\right|$, where Vol_{it} is the USD denominated traded volume for stock i on day t. I expect that, the more substitutable the markets are, the larger the incentive for market makers to match the other market's liquidity and, hence, the larger the liquidity commonality.

Koch et al. (2016) showed that a large share of institutional ownership in a stock, in particular by mutual funds, results in a heightened co-movement of the stock's liquidity to the market's. I test for this channel by controlling for the relative share of mutual fund ownership, measured as the ratio between the cumulative mutual fund ownership and the market capitalization of the stock. I expect the variable $Mutual_{it}$ to be positively correlated with liquidity commonality.

I expect commonality in trading activity to be one of the drivers of my left-hand side variable. I measure the amount of correlated trading as $R^2_{Vol,it}$, the R^2 of Equation 3, estimated using the traded amount Vol_{it} instead of L_{ith}. Finally, as in Hameed et al. (2010), I expect commonality in liquidity to be higher in times of market distress, which I measure by the level of the Vix_t index, by the return of the market, measured as the change in the S&P500 index, and by the return of each stock, orthogonalized to the market factor.

V The Results

My central hypothesis is that more intense activity by arbitrageurs leads to a tighter commonality between the market liquidities of the cross-listed stocks in the venues where they are traded. In this section, I show, first, that the daily arbitrage measure Arb_{it} captures arbitrageur's activity well. Second, I obtain a set of results relating arbitrageurs' activity to the liquidity correlation by considering simple univariate analyses. Third, I proceed to rule out alternative channels with a multivariate regression analysis.

V.A Arbitrage Opportunities and Arbitrage Activity

In the remainder of the paper, I interpret the existence of a large amount of arbitrage opportunities, Arb_{it}, as lack of arbitrage activity on stock i and day t. While determining the origin of the mispricing is beyond the scope of this study, I nonetheless need to show that Arb_{it} captures the arbitrageurs' activity, or lack thereof, and that arbitrageurs engage in the arbitrage at hand.

As first supporting evidence, I expect a large number of arbitrage opportunities, i.e., lack of arbitrageurs' activity, to arise when funding liquidity is the lowest, consistent with the findings in Mitchell, Pedersen, and Pulvino (2007): Arbitrageurs would have taken advantage of the mispricing if they had had available capital. I expect that, when it is harder for them to obtain funding liquidity, arbitrageurs cannot take advantage of all profitable arbitrage opportunities. To test this hypothesis, I regress Arb_{it} on two quantities previously used in the literature to measure the availability of capital to arbitrageurs, namely the volatility index Vix_t and the noise measure $Noise_t$ (put forward by Hu, Pan, and Wang, 2013). I expect periods of limited funding liquidity to coincide with periods of frequent arbitrage opportunities.

To further link my measure to the presence of arbitrageurs, I turn to the literature on high-frequency trading. Due to the short duration of the availability of the arbitrage opportunities, and based on the finding in Budish et al. (2015) and Kirilenko, Kyle, Samadi, and Tuzun (2016) that high-frequency traders engage in arbitrage trades between the E-mini S&P 500 futures contract and securities linked to it by an arbitrage relation—i.e., the underlying stocks or the index exchange traded fund, SPY—I expect arbitrageurs to be high-frequency traders.[15] Therefore, I need to show that measures of high-frequency trading activity are negatively correlated with the number of arbitrage opportunities, i.e., more high-frequency trading activity leads to fewer outstanding arbitrage opportunities. I measure high-frequency traders' activity, consistently with the previous literature, as the percentage of messages sent to the exchange that did not result in trades.[16]

Finally, to show that traders actually engage in arbitrage trades between cross-listed stocks, I exploit the legal framework regulating the naked shorting of a stock, RegSHO. According to RegSHO rule 200(g), a broker or a dealer needs to mark all sell orders as "long", "short", or "short exempt", depending on the ownership status of the seller. Rule 201(d)(4) regulates sell orders that are aimed at "profit[ing] from a current price difference between a security on a foreign securities market and a security on a securities market subject to the jurisdiction of the United States" be marked as "short exempt". Therefore, I expect that the fraction of short sales that are marked

[15]Biais and Foucault (2014) point out that arbitrage is a trading style where very low latency is needed. Rösch, Subrahmanyam, and van Dijk (2016) and Brogaard, Hendershott, and Riordan (2014) show that market efficiency is associated with an increase in algorithmic trading.

[16]I calculate the measure for the US market using the ITCH dataset provided by the NASDAQ. For the Canadian market, I employ the number of quote updates and number of trades and calculate a similar measure.

as "exempt" for stock i at time t, E/S_{it}, be positively correlated with the number of arbitrage opportunities that took place because the price of the US stock exceeded that of its Canadian counterpart. I quantify this occurrence as $Arb_{it}^{US} = \frac{1}{S}\sum_{1}^{S} I\left[\max\left[Bid_{US} - \frac{Ask_{CA}}{Bid_{FX}}, 0\right] > 0\right]$. Similarly, I expect E/S_{it} to be negatively correlated with the number of arbitrage opportunities that arise because the price of the Canadian stock exceeds that of its US counterpart, which I quantify as $Arb_{it}^{CA} = \frac{1}{S}\sum_{1}^{S} I\left[\max\left[\frac{Bid_{CA}}{Ask_{FX}} - Ask_{US}, 0\right] > 0\right]$, where $Arb_{it} = Arb_{it}^{US} + Arb_{it}^{CA}$.

I estimate

$$Arb_{it} = \alpha_i + \alpha_t + \delta' \mathbf{X_{it}} + \epsilon_{it} \tag{4}$$

where I allow for stock or time fixed-effects and substitute Arb_{it} with Arb_{it}^{US} or Arb_{it}^{CA} in some specifications. The results are reported in Table II.

Insert Table II here.

In Specification 1 of Table II, I show that the parameters related to both funding liquidity measures are positive and significant, implying that arbitrage opportunities are more common when funding liquidity is scarce. The parameter of 0.001 on Vix_t can be interpreted as follow: An increase of 3 units in the Vix_t index, corresponding to about a two standard deviation change, increases the arbitrage opportunities by 30 seconds per day/stock (the median Arb_{it} is 5 minutes). Similarly, a two standard deviation hike in $Noise_t$ increases the arbitrage opportunities by 50 seconds per day/stock. These findings support the conjecture that arbitrage opportunities are left unexploited when funding constraints bind.

In Specification 2 of Table II, I focus on the identity of the arbitrageurs. If my hypothesis that the arbitrage is taken advantage of by fast traders is correct, I should expect arbitrage opportunities to be few when high-frequency traders are most active. The regression results confirm my expectation, as the parameters for both HFT_{it}^{CA} and HFT_{it}^{US} are negative and significant.

Finally, Specification 3 allows me to claim that market participants trade on the arbitrage opportunities between cross-listed stocks. When the stock traded in the US is more expensive than its Canadian counterpart, the arbitrageur would sell short the stock in the US and purchase its Canadian counterpart, to lock in a risk-less profit. Consistently, Arb_{it}^{US} is increasing in the ratio of "short exempt" to "short" trades. Traders can classify their trade as "short exempt" if they are taking advantage of a mispricing between cross-listed securities. As the US stock becomes more expensive, arbitrageurs short the stock without owning it and can classify their trade as "short exempt", as long as they contemporaneously close their position by executing the opposite trade on the foreign market. Similarly, I expect E/S_{it} to be negatively related to Arb_{it}^{CA}, since the arbitrageur would not sell the cheaper of the stocks—the stock traded in the US, in this case—but, rather, buy it.[17] Specification 4 in Table II shows that my expectation is correct, as Arb_{it}^{CA} decreases in E/S_{it}.

[17]Previous literature has hypothesized that "short exempt" stocks are used by market makers to provide liquidity when a large buying pressure hits the market and their inventory is thin. In the Appendix, I address the concern that

V.B Univariate Analysis

After validating my measure of arbitrage activity, I turn to the main hypothesis that I am investigating and have laid out in Proposition 1. First, I aim to show that, consistent with my interpretation of the Arb_{it} measures, the returns of the cross-listed stocks are more highly correlated when the arbitrageurs are active on the market. Second, I want to test that liquidity commonality, i.e., the correlation between the market liquidities of securities connected by arbitrage, is higher when arbitrageurs are active on the market.

For each day and stock-pair, I aggregate the price of the cross-listed stocks at 15 different frequencies, ranging from one second to an hour. I then calculate the correlation between changes in prices in the two markets and repeat the same calculations for changes in the bid-ask spread, for each day and stock.

I split the sample of about 30,000 observations into two groups of stock-days, based on whether Arb_{it} is above or below the sample median of 0.013. In Figure 3 I plot the median correlation, for each sampling frequency, of the returns and liquidity changes in Panels A and B, respectively. Stock-days with arbitrage opportunities above the median, i.e., with lower arbitrageurs' activity, are represented by the line in red, while stock-days with high arbitrage activity, i.e., with Arb_{it} below its median, are represented by the line in blue. Table III reports means and medians of the return and liquidity changes correlations, separately for days with Arb_{it} above and below its median. Furthermore, in the "Diff" column, I report the difference between the medians (means) of the two groups, together with the statistical significance of a Wilcoxon signed rank (t-) test for their difference.[18]

Insert Figure 3 here.

Insert Table III here.

The correlation in return—which, when ignoring transaction costs, should be 100% to avoid the rise of arbitrage opportunities—is significantly higher in days of heightened activity by arbitrageurs, compared to days with more arbitrage opportunities. This result is intuitive, as a larger instantaneous correlation means a faster convergence in prices. When arbitrageurs are active, the correlation reaches 90% within less than three minutes, while it takes more than 4 minutes, or 67% longer, for the correlation to reach the same level for days with more untapped arbitrage opportunities. Panel A of Table III indicates that, while the medians are significantly different for each

E/S_{it} captures liquidity provision by market makers rather than arbitrage activity by splitting the sample in days with large selling and buying pressure on the two markets, and show that my results still hold. In the Appendix, I also conduct an analysis similar to that in Specification 3 at a high frequency, establishing that in any given second, the probability that a short sale is marked as "exempt", conditional on the sale taking place, is larger when the stock is more expensive in the US. Equivalently, it is more likely that the US price exceeds that of the Canadian counterpart, conditional on a short sale taking place, if it is marked as "exempt".

[18]To address the discreteness of the bid-ask spread, I calculate rank-based (Pearson) correlations. Similar results are obtained if Spearman correlations are calculated and if I employ alternative arbitrage measures to split my sample.

time frame, the means are significantly different for only up to five minutes. For intervals larger than ten minutes, the mean correlations for days with high arbitrage activity are indistinguishable from those in days with more arbitrage opportunities. The findings above fall squarely in line with the expectation that arbitrageurs ease price discovery, conditional on Arb_{it} being a measure of arbitrage activity, and I take them as a further confirmation of the validity of my measure.

Repeating the analysis above for changes in bid-ask spread, however, constitutes a direct test of the second part of Proposition 1, i.e., my hypothesis that arbitrageurs contribute to a tighter commonality in liquidity. Panel B of Figure 3 shows that, when arbitrageurs are very active on the market, changes in the bid-ask spread for the Canadian market are much more highly correlated with those in the US market. The result holds at any time frequency and the difference in correlation does not disappear within the time frame I consider, although it diminishes in relative terms.

In Table III, I test for the statistical significance between the median correlations that I reported in Panel B of Figure 3, and the statistical significance between the corresponding means. Panel B shows that the differences in liquidity changes correlations between days with large arbitrage activity, and days with small arbitrage activity, are substantial. The median correlation at 30 minutes, for instance, is 19% for stock-days with high Arb_{it} while it is more than twice as large at 46% on stock-days with low Arb_{it}. Therefore, the correlation in liquidity changes is significantly higher for stock-days with a small amount of untapped arbitrage opportunities, compared to days when my measures indicate arbitrageurs are not active on the market. This holds true for both the median and mean. These differences, moreover, are statistically significant at the 1% level for every frequency, while the difference in means for return correlations are statistically significant only up to the five minutes frequency.

While the results above are consistent with my expectations, a limitation of the univariate analysis is that it does not address alternative explanations for what is causing a larger correlation between liquidity measures for the different counterparts of cross-listed stocks, on days of heightened arbitrage activity. While the latter is the objective of the next subsection, I make a further effort to address the concern that my results might be driven by few days when, e.g., a lack of funding liquidity is causing both markets to dry up and, contemporaneously, arbitrage opportunity to arise, or might be driven by few stocks, e.g., that are solely traded in one market, leading to low commonality and low liquidity, impeding arbitrage.

In Table IV I show statistics similar to those in Table III, with the difference that the observations are split, within each day, between stocks with Avg_{it} above and below that day-specific median (rather than the overall sample median, as for the analysis in Table III). Each day, therefore, is equally represented in the "Low Arb_{it}" and "High Arb_{it}" groups.

Insert Table IV here.

The results are virtually unchanged, showing that the findings are not driven by a few time-series outliers. Namely, holding time-varying variables constant, the median correlation in liquidity changes at a one-minute frequency, for instance, increases three-fold between stocks that have low arbitrage activity and stocks that have large arbitrage activity. As a further robustness test of the univariate results, I repeat the same analysis, this time by splitting the observations based on whether Arb_{it} is above or below the stock-specific median, thus forcing each stock to be equally represented in the "Low Arb_{it}" and "High Arb_{it}" groups, hence focussing on time-varying, rather than cross-sectionals, differences. Table V shows these results.

Insert Table V here.

While the magnitude of the differences is smaller, holding the cross-section constant, days with high arbitrage activity still show larger liquidity commonality (and return correlation) compared to days with a vast amount of arbitrage opportunities, and the differences in medians and means are significant at the 1% level, up to one hour. For example, holding cross-sectional differences fixed, the correlation in liquidity changes at a one-minute frequency on days with high arbitrage activity is 12% higher than on days with low arbitrage activity. Interestingly, the difference between mean return correlations is only significant up to five seconds, suggesting that most of the variation in arbitrage activity comes from cross-sectional, rather than time-series, determinants. In the Appendix, I repeat the analysis from Table V, using the lagged value of Arb_{it} to address the issue of contemporaneity and find that the results are unchanged.

V.C Multivariate Results

In this subsection, I further elaborate on the relationship between liquidity co-movement between securities connected by arbitrage and arbitrageur activity. I do so by turning to multivariate analysis and determining the effect of alternative channels that drive liquidity commonality. I regress $R^2_{BA,it}$, derived in Subsection IV.B, on Arb_{it} and the sets of controls outlined in Subsection IV.C.[19]

Since both $R^2_{BA,it}$ and Arb_{it} are non-negative variables bound between zero and one and are highly non-normally distributed, I follow Chordia, Roll, and Subrahmanyam (2002) and substitute them with their Box-Cox transformation. Namely, I replace $R^2_{BA,it}$, in the regressions, by $\frac{(R^2_{BA,it})^{\lambda}-1}{\lambda}$, where λ is estimated so that the transformed variable is as close to normality as possible. I repeat this transformation separately for each commonality in liquidity and arbitrage measure.

An alternative to this method employed in the literature is transforming the variables with the log- or logistic-transformation. In the Appendix, I show that the residuals behave much better when the Box-Cox transformation is used, compared with the other alternatives. To keep my results comparable to the literature, I report my main results using the log-transform as well, which delivers very similar results. The log-transformation is a special case of the Box-Cox, when λ

[19] I test all the arbitrage and liquidity commonality measures for unit root following the methodology for panel data developed in Im, Pesaran, and Shin (2003), and I can reject the null of non-stationarity at the 1% level, for each of the variables.

tends to zero. My λ estimates are very close to, yet different, from, zero, allowing me to interpret the coefficient on the variable of interest as an elasticity.

I estimate several specifications of a panel analysis with time- and/or stock-fixed effects, as the one in Equation 5, with the transformed $R^2_{BA,it}$ on the left-hand side, and the transformed Arb_{it} and the controls on the right-hand side, where $\mathbf{X_{it}}$ includes the controls.

$$R^2_{BA,it} = \alpha + \beta Arb_{it} + \delta' \mathbf{X_{it}} + \alpha_i + \alpha_t + \epsilon_{it} \tag{5}$$

On top of the variables I described in Subsection III.B, I include the quoted spread BA^{US}_{it}, which I believe to be positively correlated with commonality. I expect that stocks that are most liquid, as defined by the bid-ask spread, show the smallest degree of commonality, since the bid-ask spread is bound by the tick size—e.g., Royal Bank of Canada., the largest company in Canada and in my sample, had a bid-ask spread larger than one cent for only 19% of the time in 2013. Zero variance in the bid-ask spread implies a null commonality.

Table VI reports the results from the estimation of different specification of Equation 5. In Specification 1, I regress $R^2_{BA,it}$ on Arb_{it}, with no other control variable or fixed effect, to gauge the first order effect of an increased presence of the arbitrageurs. The estimates for Arb_{it} are negative, as expected: more arbitrage activity, i.e., fewer arbitrage opportunities, imply a larger co-movement in liquidity between the stock traded in the US and the stock traded in Canada. The parameter is large in magnitude and significance: a 10% increase in the amount of arbitrage opportunities results in a 2% lower commonality between a stock's liquidity in the US and the liquidity of that same stock in Canada. The t-test, resulting from standard errors clustered at the company level, and thus robust to cross-stocks heteroskedasticity and within-stock auto-correlation in residuals, is above 10 in magnitude, indicating a very large statistical significance.

Insert Table VI here.

Commonality in liquidity and arbitrage opportunities can be driven by underlying factors such as, for example, funding liquidity or market-wide demand shocks. In Specification 2, I add time-fixed effects to the estimation, to control for time series drivers affecting all stocks equally. The parameter estimate for Arb_{it} is virtually unchanged, suggesting that my results are driven more by the cross-section rather than the time-series dimension of my analysis. In Specification 3 I add the bid-ask spread as a control and verify my expectation that stocks that are most liquid show the smallest degree of commonality, as the parameter for BA^{US}_{it} positive and significant. When including the bid-ask spread on the right-hand side, the magnitude and significance of the parameter for Arb_{it} is reduced. This follows from my working definition of arbitrage. Considering Panel A of Figure 1, for example, it is intuitive that, holding everything constant, the smaller the bid ask spread, the smaller the price change that is needed for an arbitrage opportunity to appear. In the robustness tests in Section VI I show that the results in this subsection are unchanged if I employ alternative definitions of arbitrage, including measures that do not include round-trip costs directly. The parameters in Specification 2 indicate that an increase in the bid ask spread of 1 cent (half a standard deviation) increases the commonality in liquidity by 3% (one-tenth of a standard deviation). The corresponding quantities for the arbitrage activity measure imply that an increase of one standard deviation in arbitrage activity increases the commonality in liquidity by one-tenth of a standard deviation.[20]

Drawing from Menkveld (2013), I expect that some market participants act as cross-market market makers while not qualifying as arbitrageurs because, for example, they do not aim at a flat inventory, possibly offering liquidity on the same side of the market rather than on opposing side, or simply being active on all four sides of the market at the same time. I control for such trading behaviour through the commonality in high-frequency activity $R^2_{HFT,it}$ in Specification 4. As expected, a higher co-movement in HFT activity positively and significantly affects the commonality in liquidity. To my knowledge, cross-border high-frequency market making has not been documented in the extant literature, and I cannot rule out that this measure captures arbitrage trading. If $R^2_{HFT,it}$ captured arbitrage activity, the results from this measure would also be consistent with my expectations.

In order to test for the channel linking the competition between market makers in the US and market makers in Canada I include, in Specification 5, the scaled absolute difference between the traded volume in the two countries. I expect that markets that are closer in terms of substitutability, from the perspective of the traders, will feature larger competition between market makers and, thus, larger liquidity commonality. While the parameter has the right sign, it is not statistically significant.

Following Brunnermeier and Pedersen (2009) and Hameed et al. (2010), I expect that the commonality in liquidity between markets is higher when the funding liquidity constraints of market participants bind. Moreover, as I show in Subsection V.A, funding liquidity is also a driver of arbitrage activity, and I need to rule out that the significance I achieve with a measure of the latter is not simply capturing the former. I proxy for the funding profile by the volatility index Vix_t, the market return $r_t^{m,US}$, and the return of the stock orthogonalized to the market $r_{it}^{\perp,US}$. Specification 6 of Table VI shows that of the three variables, the parameter for Vix_t is positive and significant, as expected, thus supporting the funding liquidity channel, while not ruling out the importance of the contribution of the arbitrageurs to the commonality in liquidity.

In Specification 7, I test for support of the findings brought forward by Koch et al. (2016), that liquidity commonality is increasing in the amount of the stock owned by mutual funds. Following a similar reasoning, I expect mutual funds to be indifferent between the trading location of the

[20]Expected sensitivities can be calculated with regard to the untransformed variable by expressing the untransformed left-hand side variable as a function of the right-hand side variables. Taking expectations, e.g., $E\left[\frac{\partial R^2_{BA,it}}{\partial BA^{US}_{it}}\right] = E\left[\left[\lambda\left(\alpha + \beta_1 Arb_{it} + \beta_2 BA^{US}_{it} + \varepsilon\right) + 1\right]^{\frac{1}{\lambda}-1}\beta_2\right]$, I bootstrap the expectation by simulating the error ε.

stock, thus affecting the commonality between markets liquidities via their portfolio reallocation. The parameter for the measure $Mutual_{it}$ is positive and significant, indicating that a 10% increase in the share of mutual fund ownership implies a 1% larger commonality between stock liquidity.

Finally, I test the hypothesis that commonality in liquidity offered by market participants is driven by a co-movement in trading patterns, or liquidity demanded. A large negative correlation in liquidity patterns could also contribute to the creation of arbitrage opportunities—if the signed traded volume in one country was negatively correlated with the signed traded volume in the other country, resulting in a large $R^2_{Vol,it}$. While signed traded volumes in the two countries are in fact mildly negative correlated (2%), the inclusion of $R^2_{Vol,it}$ as a right-hand side, with a positive and significant coefficient, does not affect the magnitude and significance of Arb_{it}.

In Specification 9, I include all the previous regressors, with the exception of the time-fixed effects. The parameters are mostly unchanged in magnitude and significance. The parameter of interest, the coefficient of Arb_{it}, is still significant at the 1% level, with a t-statistic near four and a negative sign, and indicating that a 10% increase in arbitrage activity results in a 1% increase in commonality in liquidity. In Specification 10, I perform a similar analysis, with the inclusion of time-fixed effects, to unchanged results.

VI Robustness Tests

In this section, I replicate the analysis in Subsection V.C and test for the robustness of my results by verifying that they are not driven by i) the functional form of the transformation, ii) the definition of arbitrage, iii) the choice of liquidity metric for which I calculate the commonality, and iv) the regression specification.

To test that my results are not driven by the choice of the Box-Cox transformation, I replicate Table VI using $Log(R^2_{BA,it})$, the log of the un-transformed commonality in the liquidity measure, as a left-hand side variable and substituting $Log(Arb_{it})$ for that same Box-Cox transformed variable on the right-hand side. The parameters for $Log(Arb_{it})$ can be interpreted as elasticities, while the coefficients of the other right-hand side variables as semi-elasticities. The results are reported in Table VII. As previously argued, the estimates in Table VI for Arb_{it} are remarkably close to those for $Log(Arb_{it})$ in Table VI. While the coefficients for the other variables are different in magnitude, the interpretation of the semi-elasticities coincides with those from Table VI.

Insert Table VII here.

The measure of arbitrage opportunities I employed is a measure of the frequency of arbitrage opportunities, i.e., the percentage of time during the day when the quotes between countries are crossed. Alternative measures, which I described in Subsection IV.A, capture the maximum and relative size of the arbitrage opportunities, $MaxRelArb_{it}$ and $RelArb_{it}$ respectively, restrict the arbitrage opportunities to be significantly large, $Arb1bp_{it}$, or capture how long each arbitrage opportunity persists, $Duration_{it}$. An alternative measure, which prescinds from the bid-ask spreads, is the half-life of a pricing shock, $HalfLife_{it}$, defined in Subsection IV.A and estimated in a co-integration setting outlined in Footnote 12. I replicate Specification 9 of Table VI, substituting alternative arbitrage measures to Arb_{it} and report the results in Table VIII. Varying the specific dimension of arbitrage opportunities that I employ does not affect the results; all the parameters are negative and significant at least at the 5% level.

Insert Table VIII here.

In Subsection III.A, I explicitly showed that the correlation in the bid-ask spread is larger, across markets, when arbitrageurs are active on the market, and I bring this prediction directly to the data by using $R^2_{BA,it}$ as a right-hand side variable. The trading activity of the arbitrageur, however, affects not only the width of the market, but other dimensions of liquidity as well. I replicate the analysis in Specification 9 of Table VI, while using the commonality in other liquidity variables, rather than the bid-ask spread, as left-hand side variables. Namely, I test how arbitrage activity affects the commonality in the relative bid-ask spread, $R^2_{RelBA,it}$, effective bid-ask spread, $R^2_{EffBA,it}$, realized bid-ask spread, $R^2_{ReaBA,it}$, and the Amihud measure, $R^2_{Amihud,it}$. The results are reported in Table IX, and show that arbitrage activity increases the amount of liquidity commonality regardless of how the latter is measured.

Insert Table IX here.

Finally, I test that my results are robust to changes in the way I specify the main regression. In Table X I replicate the results in Specification 9 of Table VI and in Table VIII, allowing for both time- and stock-fixed effects. Five out of six of my arbitrage measures are significant at the 10% level or better. Interestingly, together with the measure of bid-ask spread, the arbitrage activity measures are the only determinants that are significant, after the inclusion of stock fixed effects, underlying the main role of arbitrageurs in determining the liquidity commonality.

Insert Table X here.

To address the potential issue of contemporaneity between Arb_{it} and $R^2_{BA,it}$, I replicate Specification 10 of Table VI and employ lagged right-hand side variables and include the lag of the dependent variable as an explanatory variable. I report the results in Table XI. $R^2_{BA,i,t-1}$ is significant at the 1% level, indicating a modest amount of auto-correlation in liquidity commonality. Five out of six measures of arbitrage activity are negative and significant at the 5% level or better, indicating that, while concerns about contemporaneity might be warranted, modifying the main specification to test for lagged effect delivers the same results as previous analyses.

Insert Table XI here.

VII Generality of the Results

I motivated the empirical results of Section V by considering, in Subsection III.A, the strategies of an arbitrageur trading between two limit order markets. While many such arbitrages exist in stock markets—i.e, American and Global Depository Receipts and the underlying stocks, Exchange Traded Funds and their components, shares that are the object of stock mergers, to mention a few—other arbitrages exist between securities that are not traded on limit-order markets, where the strategies I envisioned would not apply. Arbitrage trades that involve over-the-counter (OTC) securities, for example, would require the arbitrageur to trade at quotes set by others, specifically market makers, since OTC markets are generally quote-driven.

Similar to the arguments brought forward by Koch et al. (2016) to motivate how trades by mutual funds result in stock liquidity commonalities, I expect that, when arbitrageurs trade contemporaneously on the different OTC markets where the securities linked by arbitrage are quoted, they would also consume liquidity in those markets. The contemporaneous trading in the OTC markets would results in the co-movement of their liquidity. In an effort to gauge the generality of the result that arbitrage activity fosters commonality in liquidity, I perform an analysis similar to that in Subsection V.C on another arbitrage relationship, linking the stock market and the OTC market for corporate bonds.

VII.A Capital Structure Arbitrage

Capital structure arbitrage involves "[trading] one security against another security issued by the same firm. For instance, to buy a corporate bond of a company while shorting the equity" (Pedersen, 2015). Arbitrageurs would take advantage, for example, of the mispricing between stocks and bond issued by a company, by trading in the two securities, betting on the eventual convergence in their value. In order to measure whether the presence of arbitrageurs has an effect on the commonality in liquidity between the two markets, I need a measure of the arbitrage activity, or lack thereof.

Following the same argument as with Arb_{it}, I measure the presence of arbitrageurs as the lack of mispricing between the equity and bond market. I employ a measure of market integration developed by Kapadia and Pu (2012). Merton's (1974) model implies that a positive (negative) shock to the value of a firm would result in an increase (decrease) in the value of both the firm's equity and its debt. Kapadia and Pu (2012) derive a measure of capital structure arbitrage opportunities as $\kappa_{i,m} = \sum_{\tau=1}^{D-1} \sum_{t=1}^{D-\tau} I\left[\Delta CDS_{i,t}^{\tau} \Delta P_{i,t}^{\tau} > 0\right]$, where D is the amount of days in period m, i is the company, $\Delta CDS_{i,k}$ is the change on day t of the credit default swap (CDS) spread for company i, and $\Delta P_{i,t}$ is the change in stock price for company i on day t. The measure counts, during each period m, for any frequency τ, how often the CDS spread and the stock return moves in the same direction. According to Merton's (1974) model, equity and debt should appreciate and depreciate at the same time, i.e., $\kappa_{i,m}$ should be zero, since an appreciation in a company's debts would translate in a decrease in its CDS spread. A large $\kappa_{i,m}$ means that the credit and equity market are not integrated, i.e., that arbitrageurs do not take advantage of the mispricing between the two markets.

I measure the liquidity for the bond market employing data for TRACE between January 2012 and December 2015. I estimate the imputed round-trip cost (IRC) as detailed in Feldhütter (2012), which measures the difference between prices paid by small traders and those paid by large traders. To measure the stock market liquidity, I employ the relative bid-ask spread, which is the closest counterpart to IRC, since it measures a trading cost for a small quantity and it is normalized across stocks (similarly, the IRC is calculated for a constant bond face value). I obtain stock prices and bid-ask spread quantities from CRSP. To calculate $\kappa_{i,m}$, I employ the stock price of the issuer of the bonds and its CDS spread (for a five-year contract), which is obtained from Markit. My final sample consists of 2686 monthly observations for 132 companies.[21]

Given the size of the sample, calculating commonality in liquidity as a regression's R^2 is not viable. Instead, I follow Karnaukh, Ranaldo, and Söderlind (2015) and regress the relative bid-ask spread for stock i in month m on the imputed round-trip cost IRC_{im}, the arbitrage opportunities measure κ_{im}, and the interaction between the two. I expect the parameter on IRC_{im} to be positive, confirming the existence of commonality in liquidity, and the parameter on the interaction to be negative, meaning that the correlation between the liquidity of stocks and bonds of the same company is smaller, when arbitrageurs are not active. I report the results in Table XII, where the standard errors are clustered by company.

Insert Table XII here.

The results in Table XII confirm my hypotheses. Specification 1 shows that stock and bond liquidity co-move, since the parameter for IRC_{im} is positive and significant. In Specification 2, the parameter for the arbitrage measure κ_{im} is not significant, however, the parameter for the interaction between IRC_{im} and κ_{im} is negative and significant, as I expected. I interpret this finding as a further confirmation of my main hypothesis: As arbitrageurs do not take advantage of arbitrage opportunities, the correlation between a company's stock liquidity and the liquidity of that company's bond is lower.

In Specification 3, I add time-fixed effects, with little effect on the coefficients. In Specification 4 and 5, I interact the bond liquidity measure IRC_{im} with measures of funding liquidity, to rule out that the results in Specifications 2 are driven by factors different than arbitrage trading and that κ_{im} is only controlling for a general lack of funding liquidity in the market. While the parameters for both $Tbill_m$ and Vix_m are positive and significant (market liquidity increases in funding liquidity),

[21]There were 2051 companies with bonds in the TRACE dataset. Calculating IRC requires at least two transaction with the same volume per day, which limits the sample. Moreover, CDS spread are available only for a fraction of all companies that issue debt.

neither of their interactions with IRC_{im} is significant, indicating that the larger commonality between stock and bond markets is not driven by market-wide liquidity shocks but, rather, by the participation of arbitrageurs as cross-market traders. Specification 6 shows that my findings are robust to including all determinants at the same time.

VIII Conclusions

Liquidity has been shown to co-move *within* markets, in the work by Chordia, Roll, and Subrahmanyam (2000), Hasbrouck and Seppi (2001), and Huberman and Halka (2001), and *across* markets, in more recent studies by Zhang, Cai, and Cheung (2009), Brockman, Chung, and Pérignon (2009), and Bongaerts, Roll, Rösch, Van Dijk, and Yuferova (2015). While previous work has shown that aggregate market liquidity is correlated across markets, I contribute to this literature by investigating the commonality in liquidity for single securities traded across different markets or otherwise connected by an arbitrage relation, and show that arbitrage activity is a key determinant of the liquidity co-movement.

I develop a simple trading model that, by analyzing the strategies available to an arbitrageur, delivers the prediction that arbitrage trading contributes to commonality in liquidity between securities connected by arbitrage. Focussing on a sample of 125 Canadian stocks cross-listed in the United States, I quantify arbitrage activity per stock-day as the frequency of arbitrage opportunities arising between two securities with identical cash flows. I support this identification by showing that the arbitrage measure depends, as expected, on known determinants of arbitrage opportunities—funding liquidity, high-frequency trading activity, and short-selling activity.

In a univariate context, I show that when arbitrage activity is high, so is the co-movement between the market liquidity of the securities linked by arbitrage. After laying out alternative determinants of commonality in liquidity between securities connected by arbitrage, with a multivariate analysis, I test that arbitrage activity is a significant determinant of commonality after controlling for all other possible channels. I verify that my results are robust to alternative definitions of liquidity commonality and arbitrage activity. Finally, to test the generality of my results, I replicate the analysis for a different arbitrage trade, involving bonds and stocks.

My contribution to the literature is of interest to a diverse set of market participants. Traders benefit from successfully determining the future liquidity level of the securities they trade in, whether they profit from a superior knowledge of the order flow, like high-frequency traders, or need to be able to rebalance their portfolios swiftly and costlessly, like institutional investors. Policy makers interested in the effect of facilitating the access by traders to a trading venue need to take into account the effect that fostering arbitrage activity has on the systematic component of liquidity. Finally, central banks need to understand the far-reaching effect that their security purchase programmes, particularly in recent years, have on the markets such as derivatives, connected to those that they target, thanks to the arbitrageurs' activity.

Appendix

Calculations for Trading Model

In the setting I describe in Subsection III.A, two securities linked by arbitrage are traded in two markets. The bid price in market 1 is $B_1 = \alpha + \varepsilon_1$ where ε_1 takes the value of -0.01, 0, or 0.01 with equal probability $\frac{1}{3}$. The ask-price is given by $A_1 = B_1 + \mu_1$ where μ_1 is equal to 0.01 or 0.02, with equal probability $\frac{1}{2}$. Similarly $B_2 = \alpha + \varepsilon_2$ and $A_2 = B_2 + \mu_2$ where ε_2 and μ_2 are independent and identically distributed to ε_1 and μ_1, respectively.

Table XIII shows the 36 possible combinations of bid- and ask-prices for the two markets, when $\alpha = 98$. After the arbitrageur has submitted a marketable or limit order, a trader arrives and hits one of the four sides of the market with equal probability.

I show here explicitly that Proposition 1 holds before the advent of the trader, when the arbitrageur only trades on crossed quotes, calculating the bid- and ask-prices following the arbitrageur's submission, and the resulting correlation between bid-ask spreads. Then, I show that Proposition 1 holds generally by reporting the quantities that are obtained when the arbitrageurs employs the strategies described in Subection III.A and accounting for the random trade by the exogenous trader. The general results are obtained through trivial yet lengthy algebra, and further details are provided upon request.

As far as the simplest case is concerned, I highlight in red in Table XIII the quotes corresponding to crossed quotes. Table XIV reports the bid and ask prices following the arbitrageur's trade and before the advent of the trader.

Insert Table XIII here.

Insert Table XIV here.

The expected quantities for the two markets after the arbitrageur's trade are:

$$E[B_1] = E[B_2] = 98 + \frac{12(-0.01) + 12(0) + 10(0.01) + 2(0)}{36} = 97.999\overline{4}$$

$$E[A_1] = E[A_2] = 98 + \frac{4(0) + 2(0.01) + 12(0.01) + 12(0.02) + 6(0.03)}{36} = 98.01\overline{5}$$

$$E[A_1 - B_1] = E[A_2 - B_2] = E[A_1] - E[B_2] = 0.016\overline{1}$$

$$E[B_1 - B_2] = 0$$

$$E[A_1 - A_2] = 0$$

The variances, covariances, and correlations between the variables are

$$
\begin{aligned}
Var\left[B_1\right] = Var\left[B_2\right] &= \frac{22(0.01)^2}{36} - E\left[B_1\right]^2 = 0.0000608 \\
Var\left[A_1\right] = Var\left[A_2\right] &= \frac{14(0.01)^2 + 12(0.02)^2 + 6(0.03)^2}{36} - \left(E\left[A_1\right] - 98\right)^2 = 0.0000802 \\
Var\left[A_1 - B_1\right] = Var\left[A_2 - B_2\right] &= \frac{15(0.01)^2 + 20(0.02)^2 + 1(0.03)^2}{36} - E\left[A_1 - B_1\right]^2 = 0.000029 \\
Cov\left[A_1, B_1\right] = Cov\left[A_2, B_2\right] &= \frac{Var\left[B_1\right] + Var\left[A_1\right] - Var\left[A_1 - B_1\right]}{2} = 0.0000558 \\
Cov\left[A_1, A_2\right] = Cov\left[B_1, B_2\right] &= \frac{1(0^2) + 4(0.01)^2 + 4(0.02)^2 + 1(0.03)^2 + 6(0 \cdot 0.01)+}{36} \\
&\quad \frac{+2(0 \cdot 0.02) + 8(0.01 \cdot 0.02) + 6(0.01 \cdot 0.03) + 4(0.02 \cdot 0.03)}{36} - \left(E\left[A_1\right] - 98\right)^2 = \\
Cov\left[A_1, B_2\right] = Cov\left[B_1, A_2\right] &= 0.0000086 \\
Cov\left[A_1 - B_1, A_2 - B_2\right] &= 0.0000043 \\
Corr\left[A_1 - B_1, A_2 - B_2\right] &= \frac{Cov\left[A_1 - B_1, A_2 - B_2\right]}{Var\left[A_1 - B_1\right]} = 0.1473
\end{aligned}
$$

As the calculations show, i) the covariance between the bid prices, ii) the covariance between ask prices and iii) the covariance between the bid-ask spreads are positive, once the arbitrageur's trading strategies are taken into consideration, compare to their baseline value of zero.

After one of the 36 combinations of quotes is drawn, the trader enters the market and hits one of the four existing quotes. The possible combinations of initial quotes and trader's actions are 144. Moreover, all correlations can be calculated before and after the arrival of the trader and before or after the order deletion by the arbitrageur. Due to the large number of cases and stages, I only report the quantities of interest, derived through trivial yet lengthy algebra.

The covariances and correlations between bid prices, ask prices, and bid-ask spreads, after the submission of limit or market orders by the arbitrageurs are:

$$
\begin{aligned}
Cov\left[A_1, A_2\right] &= 0.0000249 \\
Corr\left[A_1, A_2\right] &= 0.3593 \\
Cov\left[B_1, B_2\right] &= 0.0000\overline{2} \\
Corr\left[B_1, B_2\right] &= 0.4000 \\
Cov\left[A_1 - B_1, A_2 - B_2\right] &= 0.0000138 \\
Corr\left[A_1 - B_1, A_2 - B_2\right] &= 0.4532
\end{aligned}
$$

The same quantities after the arrival of the exogenous trader and the execution of her order, when no arbitrageur is present, are:

$$\begin{aligned}
Cov\left[A_1, A_2\right] &= -0.0000063 \\
Corr\left[A_1, A_2\right] &= -0.0566 \\
Cov\left[B_1, B_2\right] &= -0.0000063 \\
Corr\left[B_1, B_2\right] &= -0.0732 \\
Cov\left[A_1 - B_1, A_2 - B_2\right] &= -0.0000250 \\
Corr\left[A_1 - B_1, A_2 - B_2\right] &= -0.5000
\end{aligned}$$

Finally, the covariances and correlation between bid prices, ask prices and bid-ask spreads, after the arrival of the exogenous trader and the execution of her order, when taking into account the arbitrageur's strategies are:

$$\begin{aligned}
Cov\left[A_1, A_2\right] &= 0.0000187 \\
Corr\left[A_1, A_2\right] &= 0.2119 \\
Cov\left[B_1, B_2\right] &= 0.0000160 \\
Corr\left[B_1, B_2\right] &= 0.2150 \\
Cov\left[A_1 - B_1, A_2 - B_2\right] &= -0.0000112 \\
Corr\left[A_1 - B_1, A_2 - B_2\right] &= -0.2017
\end{aligned}$$

The correlation between bid quotes across markets, after the arbitrageur has submitted limit or market orders, is 40%, which results from lowering the higher bid price and raising the lower bid price, by the submission of limit and market orders. The same quantity for the ask prices is positive, yet smaller, due to the larger volatility of the bid prices, following from the presence of μ_1 and μ_2. The correlation between bid quotes, by construction, if the arbitrageur is not active on the market, is 0. The correlation between bid-ask spreads, after the limit and market order submission by the arbitrageur is 45%. By construction, the correlation between bid-ask spreads in the absence of the arbitrageur is zero.

After the trade initiated by an exogenous trader, the liquidity of the two markets is bound to be negatively correlated, since the market that is hit will exhibit a larger bid-ask spread, while the other market is unchanged. The correlation between bid-ask spreads is -50%, when the arbitrageur is not present (which follows from the fact that the bid-ask spread in either market with equal probability will increase, while the other will remain unchanged). When the arbitrageur posts limit order and therefore could be providing liquidity to the market hit by the trader, while taking liquidity from the opposite market, the correlation between bid-ask spreads is less negative (-20%), as stated in Proposition 1.

List of Companies

This Appendix features the full set of names of cross-listed companies, together with their corresponding tickers in the US (US) and in the Canadian market (CA), their market capitalization in millions of US Dollar as of December 31, 2015, and the industry in which the companies operate.[22]

US	CA	Name	Capitalization	Industry
AAU	AMM	Almaden Minerals	75	Mining, Quarrying, Oil and Gas
AAV	AAV	Advantage Oil & Gas	730	Mining, Quarrying, Oil and Gas
ABX	ABX	Barrick Gold	20,527	Mining, Quarrying, Oil and Gas
AEM	AEM	Agnico Eagle Mines	4,576	Mining, Quarrying, Oil and Gas
AEZS	AEZ	Aeterna Zentaris	43	Manufacturing
AG	FR	First Majestic Silver	1,147	Mining, Quarrying, Oil and Gas
AGI	AGI	Alamos Gold	1,547	Mining, Quarrying, Oil and Gas
AGU	AGU	Agrium	13,222	Manufacturing
AKG	AKG	Asanko Gold	140	Mining, Quarrying, Oil and Gas
AT	ATP	Atlantic Power	417	Utilities
AUQ	AUQ	Aurico Gold	906	Mining, Quarrying, Oil and Gas
AUY	YRI	Yamana Gold	6,486	Mining, Quarrying, Oil and Gas
AXU	AXR	Alexco Resource	79	Mining, Quarrying, Oil and Gas
AZC	AZC	Augusta Resource	206	Mining, Quarrying, Oil and Gas
BAM	BAM.A	Brookfield Asset Mgm	23,824	Construction
BBRY	BB	Blackberry	3,902	Manufacturing
BCE	BCE	B C E	33,585	Information
BIN	BIN	Progressive Waste	2,849	Administrative, Support, Waste, Remediation
BMO	BMO	Bank of Montreal	42,941	Finance and Insurance
BNS	BNS	Bank of Nova Scotia	75,569	Finance and Insurance
BPO	BPO	Brookfield Office Prop.	9,723	Real Estate and Rental and Leasing
BRP	BRP	Brookfield Residential Prop.	2,834	Real Estate and Rental and Leasing
BTE	BTE	Baytex Energy	4,893	Mining, Quarrying, Oil and Gas
BTG	BTO	B2Gold	1,380	Mining, Quarrying, Oil and Gas
BXE	BXE	Bellatrix Exploration	1,253	Mining, Quarrying, Oil and Gas
CAE	CAE	C A E	3,324	Manufacturing
CCJ	CCO	Cameco	8,212	Manufacturing
CLS	CLS	Celestica	1,700	Manufacturing
CM	CM	Canadian Imperial Bank	34,051	Finance and Insurance
CNI	CNR	Canadian National Railway	190,655	Transportation and Warehousing
CNQ	CNQ	Canadian National Resources	36,731	Mining, Quarrying, Oil and Gas
COA	COA	Coastal Contact	267	Retail Trade
COT	BCB	COTT	759	Manufacturing
CP	CP	Canadian Pacific Railway	26,505	Transportation and Warehousing
CTRX	CCT	Catamaran	9,796	Information
CVE	CVE	Cenovus Energy	21,651	Mining, Quarrying, Oil and Gas
DDC	DDC	Dominion Diamond	1,222	Mining, Quarrying, Oil and Gas
DNN	DML	Denison Mines	542	Mining, Quarrying, Oil and Gas
DRWI	DWI	Dragonwave	69	Manufacturing
DSGX	DSG	Descartes System Group	842	Information
ECA	ECA	Encana	13,357	Mining, Quarrying, Oil and Gas
EGO	ELD	Eldorado Gold	4,071	Mining, Quarrying, Oil and Gas
ENB	ENB	Enbridge	36,179	Transportation and Warehousing
EQU	EQU	Equal Energy	191	Finance and Insurance
ERF	ERF	Enerplus	3,674	Finance and Insurance
EXFO	EXF	E X F O	137	Manufacturing
EXK	EDR	Endeavour Silver	362	Mining, Quarrying, Oil and Gas
FNV	FNV	Franco Nevada	5,984	Mining, Quarrying, Oil and Gas
FSM	FVI	Fortuna Silver Mines	361	Mining, Quarrying, Oil and Gas
FSRV	FSV	Firstservice	1,374	Real Estate and Rental and Leasing
GG	G	Goldcorp	17,600	Mining, Quarrying, Oil and Gas
GIB	GIB.A	Groupe C G I	9,234	Professional, Scientific, and Technical Services
GIL	GIL	Gildan Activewear	6,505	Manufacturing
HBM	HBM	Hudbay Minerals	1,416	Mining, Quarrying, Oil and Gas
HYGS	HYG	Hydrogenics	166	Manufacturing
IAG	IMG	Iamgold	1,252	Mining, Quarrying, Oil and Gas
IMAX	IMX	IMAX	1,989	Manufacturing
IMO	IMO	Imperial Oil	37,527	Mining, Quarrying, Oil and Gas

[22]Blackberry changed ticker during the 2013 trading year, from RIMM (RIM) to BBRY (BB), in the US (Canada).

IMRS	IM	Imris	82	Manufacturing
IPCI	I	Intellipharmaceutics	78	Manufacturing
JE	JE	Just Energy	1,026	Utilities
KGC	K	Kinross Gold	5,002	Mining, Quarrying, Oil and Gas
MDCA	MDZ.A	M D C Partners	1,237	Professional, Scientific, and Technical Services
MEOH	MX	Methanex	5,670	Manufacturing
MFC	MFC	Manulife Financial	36,372	Finance and Insurance
MGA	MG	Magna International	18,341	Manufacturing
MITL	MNW	Mitel Networks	544	Manufacturing
MVG	MAG	M A G Silver	312	Mining, Quarrying, Oil and Gas
NAK	NDM	Northern Dynasty Minerals	124	Mining, Quarrying, Oil and Gas
NCQ	NCQ	Novacopper	80	Mining, Quarrying, Oil and Gas
NDZ	NDN	Nordion	526	Health Care and Social Assistance
NEPT	NTB	Neptune Tech & Bioresources	174	Manufacturing
NG	NG	Novagold Resources	803	Mining, Quarrying, Oil and Gas
NGD	NGD	New Gold	2,640	Mining, Quarrying, Oil and Gas
NOA	NOA	North American Energy	203	Mining, Quarrying, Oil and Gas
NSU	NSU	Nevsun Resources	665	Mining, Quarrying, Oil and Gas
NVDQ	NDQ	Novadaq Technologies	906	Manufacturing
ONCY	ONC	Oncolytics Biotech	119	Manufacturing
OTEX	OTC	Open Text	5,432	Professional, Scientific, and Technical Services
PAAS	PAA	Pan American Silver	1,771	Mining, Quarrying, Oil and Gas
PBA	PPL	Pembina Pipeline	11,029	Transportation and Warehousing
PCOM	PTS	Points International	383	Professional, Scientific, and Technical Services
PDS	PD	Precision Drilling	2,589	Mining, Quarrying, Oil and Gas
PGH	PGF	Pengrowth Energy	3,220	Mining, Quarrying, Oil and Gas
POT	POT	Potash Corp Saskatchewan	28,456	Mining, Quarrying, Oil and Gas
PPP	P	Primero Mining	513	Mining, Quarrying, Oil and Gas
PVG	PVG	Pretium Resources	542	Mining, Quarrying, Oil and Gas
PWE	PWT	Penn West Petroleum	4,083	Mining, Quarrying, Oil and Gas
QLTI	QLT	Q L T	284	Manufacturing
RBA	RBA	Ritchie Bros Auctioneers	2,451	Professional, Scientific, and Technical Services
RCI	RCI.B	Rogers Communications	18,260	Information
REE	RES	Rare Element Resources	75	Finance and Insurance
RIC	RIC	Richmont Mines	40	Mining, Quarrying, Oil and Gas
RIOM	RIO	Rio Alto Mining	295	Mining, Quarrying, Oil and Gas
RY	RY	Royal Bank of Canada	96,886	Finance and Insurance
SA	SEA	Seabridge Gold	333	Mining, Quarrying, Oil and Gas
SAND	SSL	Sandstorm Gold	428	Management of Companies and Enterprises
SJR	SJR.B	Shaw Communications	10,524	Information
SLF	SLF	Sun Life Financial	21,455	Finance and Insurance
SLW	SLW	Silver Wheaton	7,217	Mining, Quarrying, Oil and Gas
SMT	SMA	Smart Technologies	91	Manufacturing
SSRI	SSO	Silver Standard Resources	562	Mining, Quarrying, Oil and Gas
STB	STB	Student Transportation	504	Transportation and Warehousing
STKL	SOY	Sunopta	665	Wholesale Trade
SU	SU	Suncor Energy	52,192	Mining, Quarrying, Oil and Gas
SVM	SVM	Silvercorp Metals	392	Mining, Quarrying, Oil and Gas
SWIR	SW	Sierra Wireless	751	Manufacturing
TAC	TA	Transalta	3,402	Utilities
TAHO	THO	Tahoe Resources	2,432	Manufacturing
TC	TCM	Thompson Creek Metals	375	Mining, Quarrying, Oil and Gas
TCK	TCK.B	Teck Resources	14,742	Mining, Quarrying, Oil and Gas
TD	TD	Toronto Dominion Bank	86,653	Finance and Insurance
TGA	TGL	Transglobe Energy	614	Mining, Quarrying, Oil and Gas
TGB	TKO	Taseko Mines	409	Mining, Quarrying, Oil and Gas
TGD	TMM	Timmins Gold	155	Mining, Quarrying, Oil and Gas
THI	THI	Tim Hortons	8,586	Accommodation and Food Services
TKMR	TKM	Tekmira Pharmaceuticals	151	Manufacturing
TLM	TLM	Talisman Energy	12,049	Mining, Quarrying, Oil and Gas
TRI	TRI	Thomson Reuters	31,033	Information
TRP	TRP	Transcanada	32,285	Transportation and Warehousing
TRQ	TRQ	Turquoise Hill Resources	3,325	Mining, Quarrying, Oil and Gas
TRX	TNX	Tanzanian Royalty	177	Mining, Quarrying, Oil and Gas
VRX	VRX	Valeant Pharmaceuticals	39,210	Manufacturing
WILN	WIN	Wi Lan	408	Manufacturing
WPRT	WPT	Westport Innovations	1,229	Manufacturing

Arbitrage Trading vs. Market Making

In Subsection V.A, I use the fraction of short trades marked as "exempt" for stock i on day t E/S_{it} to show that traders take advantage of arbitrage opportunities, since RegSHO Rule 201(d)(4) lists cross-country arbitrage trading as one of the reasons a trader can claim to classify her trade as "short exempt".

Another reason why trades can be claimed to be "short exempt" is if the "[t]he short sale [...] is by a market maker to offset customer odd-lot orders or to liquidate an odd-lot position", which is why E/S_{it} has been used in previous studies to capture market makers' involvement in trading. This second reason short trades can be marked as exempt would undermine the interpretation of E/S_{it} in Subsection V.A: If traders were exerting an unusually large buying pressure on the US share, market makers may have to resort to shorting in order to fulfil the buying interest. At the same time, the large buying pressure might push the bid-price for the US share above the ask-price of its Canadian counterpart. That is, a large realization of E/S_{it} could be observed contemporaneously with a mispricing, even when no arbitrage trading is taking place.

In order to verify the intuition that for the sample of cross-listed stocks E/S_{it} captures arbitrage activity, rather than market making, I double-sort the observations for each stock into quartiles based on the signed amount traded in the US and in Canada and repeat the analysis in Specification 3 and 4 of Table II separately, for each of the 16 subsets. If E/S_{it} was measuring solely market making activity, i.e., short selling by market makers when they face a large buying pressure, I would not expect to observe a larger E/S_{it} when the US stock is more expensive than its Canadian counterpart and contemporaneously traders are selling the US stock (that is, when market makers are facing a selling pressure and should be buying the stock, rather than selling it). The parameter for S/E_{it} for the regressions in the 16 groups is reported in Table XV where Panel A (B) reports the results for Specification 3 (4).

Insert Table XV here.

All the parameters in Table XV are statistically significant (with one exception) and of sign consistent with my expectation and with the analysis in Subsection V.A. The parameters in column 1 indicate that even when only considering the 25% days for each stock with the smallest (i.e., most negative) US trading volume—i.e., when market makers would be facing a selling pressure, rather than a buying pressure, and would be buying rather than selling, or shorting, the stock—the same result as in Table II is obtained. That is, when the US stock is more expensive, traders sell it short and mark their trades as "short exempt", consistent with arbitrage trading strategies.

Since RegSHO specifically mentions the requirement that the market maker face an odd-lot trade, I repeat the analysis in Specification 3 and 4 of Table II including as right-hand side variable the ratio of odd-lot trades that took place on NASDAQ for stock i on day t. The parameter on that variable is negative and significant—more odd-lot trades, fewer arbitrage opportunities, suggesting that arbitrage opportunities might originate from small, stale, odd-sized quotes that the arbitrageur takes advantage of—while the sign and significance of the parameter for E/S_{it} are unchanged. These further results are available upon request.

High-Frequency Results

While the results above establish that "short exempt" sales are used more when the US stock is more expensive than its Canadian counterpart, regardless of the buying or selling pressure in the two markets, the analysis is conducted at a daily level and other factors could contribute to the results. Thanks to the availability of second stamped quotes and trade data, I can determine whether the same relationship holds at a much higher frequency.

I determine, for each trading second and stock, whether a trader sold the stock short, whether it was "short exempt", and whether an arbitrage was present on the market. Arguing that arbitrageurs are more likely to use short exempt trades when the stock in the US is more expensive than its Canadian counterpart and an arbitrage is present, is tantamount to verifying that

$$\Pr\left[E_{its} = 1 \mid Arb_{its}^{US} = 1, S_{its} = 1\right] > \Pr\left[E_{its} = 1 \mid S_{its} = 1\right] \tag{6}$$

or, alternatively, that the price of the US stock is more likely to be higher than its Canadian counterpart if, conditional on a short sale taking place, that short sale is "exempt":

$$\frac{\Pr\left[E_{its} = 1, Arb_{its}^{US} = 1, S_{its} = 1\right]}{\Pr\left[Arb_{its}^{US} = 1, S_{its} = 1\right]} > \frac{\Pr\left[E_{its} = 1, S_{its} = 1\right]}{\Pr\left[S_{its} = 1\right]} \tag{7}$$

$$\Pr\left[Arb_{its}^{US} = 1 \mid E_{its} = 1, S_{its} = 1\right] > \Pr\left[Arb_{its}^{US} = 1 \mid S_{its} = 1\right]. \tag{8}$$

I calculate the empirical counterparts to the theoretical quantities in Equation 7 and verify that Equation 6 holds by calculating $\Pr\left[E_{its} = 1 \mid Arb_{its}^{US} = 1, S_{its} = 1\right] - \Pr\left[E_{its} = 1 \mid S_{its} = 1\right]$ and showing that this amount is positive. I calculate the quantities in Equations 7 and 6 for each day t and report the quantiles of their distributions in Table XVI, where the variable "Difference" corresponds to $\Pr\left[E_{its} = 1 \mid Arb_{its}^{US} = 1, S_{its} = 1\right] - \Pr\left[E_{its} = 1 \mid S_{its} = 1\right]$.

Insert Table XVI here.

As expected, the difference variable is mostly positive. The t-test statistics for the difference in conditional probabilities $\Pr\left[E_{its} = 1 \mid Arb_{its}^{US} = 1, S_{its} = 1\right] - \Pr\left[E_{its} = 1 \mid S_{its} = 1\right]$ to be zero is $\frac{0.1602}{0.0722/\sqrt{247}} = 34.9$, which is significant at the 1% level. This result confirms that the probability of a short sale to be "short exempt" is higher when the price of the US stock exceeds that of its Canadian counterpart and, alternatively, that, conditional on a short sale taking place, that same arbitrage is more likely if the short sale was "short exempt". We take the results in this subsection as further confirmation that S/E_{it} measures arbitrage activity for cross-listed stocks.

Tranformations Comparison and Residual Normality

In Subsection V.C, I estimate the panel regression on the Box-Cox–transformed variables and argued that this transformation delivers better distributed residuals, compared to alternative transformations employed in the literature, such as the log- and logistic-transformation. In Table XVII, I report several percentiles, kurtosis, and skewness for a standard normal and the (standardized) residuals of estimating the following three regressions

$$\frac{{R^2_{BA,it}}^{\lambda} - 1}{\lambda} = \alpha + \beta \frac{Arb_{it}^{\lambda} - 1}{\lambda} + \varepsilon_2 \tag{9}$$

$$\log\left(R^2_{BA,it}\right) = \alpha + \beta \log\left(Arb_{it}\right) + \varepsilon_3 \tag{10}$$

$$\log\left(\frac{R^2_{BA,it}}{1 - R^2_{BA,it}}\right) = \alpha + \beta \log\left(\frac{Arb_{it}}{1 - Arb_{it}}\right) + \varepsilon_4. \tag{11}$$

Insert Table XVII here.

Equations 9, 10, and 11 represent regressions where I explicitly state how the data were transformed via the Box-Cox, log-, and logistic-transformation, respectively. The last two columns of Table XVII indicate that the residuals obtained from the Box-Cox transformation are distributed much more closely to the normal distribution than the alternatives, followed by the logistic-transformation. Normality tests, like that by Jarque and Bera, reject the hypothesis of normality for all transformations, but indicate that the Box-Cox transformation performs better than the logistic-, which in turns performs better than the log-transformation.

Univariate using Lagged arb

I repeat the analysis from Table V, using the lagged value of Arb_{it} to separate between high and low arbitrage environments and report the results in Table XVIII. Interestingly, the significance differences in medians do not hold for returns, while they are unchanged for the correlation in liquidity changes.

Insert Table XVIII here.

Accounting for Maker-Taker Fees

When calculating the profit available to an arbitrageur, all trading fees should be taking into account, including maker-taker fees, i.e., fees from taking liquidity from the market with market orders or, alternatively, rebates for providing liquidity to the market with limit orders. While arbitrageurs might use both limit and market orders to profit from a mispricing, the strategy the Arb_{it} measure is built upon consists of using two market orders, to take advantage of the mispricing in case of crossed quotes. This strategy would incur the highest amount of fees, since the arbitrageur is taking liquidity from both markets.

To take into account the presence of these fees, I calculate an alternative version of AO_{its}

$$AO_{its}^{MTF} = \max\left[\frac{Bid_{CA}}{Ask_{FX}} - Ask_{US} - 0.006, Bid_{US} - \frac{Ask_{CA}}{Bid_{FX}} - 0.006, 0\right]$$

which is used to calculate a new daily arbitrage opportunity measure, Arb_{it}^{MTF}. The trading profits are required to be larger than 0.006 since both Foucault, Kadan, and Kandel (2013) and Malinova and Park (2015) report that exchanges charged up to 0.003 per trade to the actor hitting or lifting a standing order. The lower bound of 0.006 is a conservative estimate since i) some exchanges charge less than 0.003 per trade, and ii) some "inverted" exchanges charge liquidity providers, rather than liquidity takers.

Requiring each arbitrage opportunity to be larger than 0.006 drastically reduces the frequency of arbitrage opportunities. About 50% of Arb_{it}^{MTF} observations are zero, compared to less than 8% of Arb_{it}. Since every transformation deals with zero observations by attributing them an arbitrary low number and the almost majority of Arb_{it}^{MTF} are null observations, I avoid transforming Arb_{it}^{MTF}. I estimate Equation 5 and replicate Table VI, regressing the untransformed $R^2_{BA,it}$ on the right-hand side variables, which include the untransformed Arb_{it}^{MTF}. Results are reported in Table XIX. Arb_{it}^{MTF} is negative and significant, as expected, in each specification. The parameter in Specification 9 for Arb_{it}^{MTF} implies an elasticity of liquidity commonality to arbitrage opportunities of -1.3%.

Insert Table XIX here.

Comparison Between FX Data Sources

To calculate arbitrage opportunities and take into account FX market liquidity, I employ the bid- and ask-quotes for the USD-CAD FX rate, as in Equation 1. The comparison between Panels A and B of Figure 2 shows the difference in arbitrage opportunities frequency obtained from using the midquote of the FX rate.

While the platform by Thomson Reuters holds the largest market share for commonwealth-based currencies, it is only one of several platforms where a trader can obtain quotes for exchange rates. Employing data from one platform, rather than data aggregated across platforms, results in ignoring better quotes available elsewhere on the market, hence biasing the bid-ask spread on the FX market upwards and Arb_{its} downwards, since large FX costs impede arbitrage. Moreover, compared to using a dataset aggregating several platforms, a single source of data can include stale or erroneous quotes, hence resulting in inaccurate arbitrage opportunities calculations.

To verify that Thomson Reuters data are representative of the FX market as a whole, I compare the foreign exchange rates I employ in the analysis to rates obtained from Olsen Data, who aggregate and filter quotes from multiple dealers. I have access to millisecond stamped data for the month of April 2013. I plot observations, averaged at a half-hour frequency, of the midquotes calculated using Thomson Reuters quotes against their counterparts obtained from Olsen Data, in Panel A of Figure 4. I similarly plot the bid-ask spreads obtained from the two sources in Panel B.

Insert Figure 4 here.

Panel A of Figure 4 shows that the midquotes obtained from the two datasets are undistinguishable from one another, with the exception of two outliers out of the 543 observations. The (rank) correlation between the two series is 99.95% (99.86%). Panel B shows that, as expected, despite its large share of the market, the liquidity is lower on the Thomson Reuters platform than on the market as a whole, as calculated by Olsen Data. The bid-ask spread on Thomson Reuters is on average 0.00017 dollars larger than its counterpart obtained from Olsen Data. This finding implies that, if any bias is present in the arbitrage opportunities measures I calculate, Arb_{its} is a conservative measure of arbitrage opportunities. The (rank) correlation between the liquidity measures obtained from the two datasets is 53.93% (27.67%). It is reassuring that periods of large market illiquidity are contemporaneous in the two datasets. While these large outliers drive a sizeable fraction of the correlation, the rank-correlation—which only considers the ordering of the observations, rather than their magnitude—is large, at 27.67%.

Tables

Table I
Descriptive Statistics

This table presents the distribution of the variables used in the analysis. The observations are day-stock specific and the sample consists of trading days from 2013 for stocks cross-listed between Canada and the United States. Panel A displays the measures of arbitrage activity, including the frequency of arbitrage opportunities Arb_{it}, their maximum relative size $MaxRelArb_{it}$ (in basis points), their average relative size $RelArb_{it}$ (in basis points), and their average $Duration_{it}$ (in seconds) for stock pair i on day t. Panel B shows the descriptive statistics of the market liquidity measures, separately for the US and Canada. The liquidity measures employed are the quoted bid-ask spread, BA_{it}, the relative bid ask spread $RelBA_{it}$, the effective bid-ask spread $EffBA_{it}$, the realized bid-ask spread $RealBA_{it}$, and the Amihud illiquidity measure $Amihud_{it}$ (in basis point per ten thousand dollars traded). The arbitrage and liquidity measures are described in detail in Subsection IV.A and IV.B, respectively. Panel C presents the descriptive statistics for the measures of liquidity commonality, which are calculated as the R^2 of stock-daily regressions of half-hour liquidity changes, as detailed in Subsection IV.B.

Panel A: Arbitrage Measures							
Variable	Mean	Std	P5	P25	Median	P75	P95
Arb_{it}	0.026	0.034	0.000	0.003	0.013	0.034	0.108
$Arb1bp_{it}$	0.018	0.029	0.000	0.001	0.005	0.020	0.089
$MaxRelArb_{it}$	7.763	8.144	0.000	2.515	4.632	10.319	26.786
$RelArb_{it}$	0.101	0.221	0.000	0.003	0.016	0.073	0.610
$Duration_{it}$	18.353	41.276	0.000	2.759	4.721	12.230	93.333
$HalfLife_{it}$	49.366	72.239	2.927	6.358	19.190	58.434	218.537
Panel B: Liquidity Measures							
Variable	Mean	Std	P5	P25	Median	P75	P95
BA_{it}^{US}	0.025	0.021	0.010	0.011	0.017	0.028	0.076
BA_{it}^{CA}	0.025	0.025	0.010	0.010	0.014	0.029	0.083
$RelBA_{it}^{US}$	0.003	0.003	0.000	0.001	0.002	0.004	0.011
$RelBA_{it}^{CA}$	0.003	0.005	0.000	0.001	0.001	0.004	0.015
$EffBA_{it}^{US}$	0.019	0.013	0.009	0.011	0.013	0.020	0.051
$EffBA_{it}^{CA}$	0.021	0.018	0.010	0.011	0.012	0.023	0.064
$ReaBA_{it}^{US}$	0.015	0.012	0.005	0.007	0.011	0.017	0.044
$ReaBA_{it}^{CA}$	−0.000	0.013	−0.016	−0.006	−0.002	0.002	0.027
$Amihud_{it}^{US}$	35.446	60.443	0.255	1.158	5.670	39.798	186.077
$Amihud_{it}^{CA}$	82.790	169.220	0.294	1.547	9.598	63.991	514.687
Panel C: Liquidity Commonality Measures							
Variable	Mean	Std	P5	P25	Median	P75	P95
$R^2_{BA,it}$	0.298	0.266	0.001	0.059	0.229	0.488	0.826
$R^2_{RelBA,it}$	0.300	0.273	0.002	0.058	0.224	0.490	0.850
$R^2_{EffBA,it}$	0.236	0.249	0.001	0.038	0.149	0.361	0.767
$R^2_{ReaBA,it}$	0.155	0.236	0.000	0.010	0.051	0.187	0.742
$R^2_{Amihud,it}$	0.223	0.272	0.001	0.023	0.104	0.332	0.892

Table II
Arbitrage Opportunities and Arbitrage Activity

This table reports tests of whether the opportunity measure Arb_{it} captures the level of arbitrage activity. I estimate different specification of the regression in Equation 4. The top row indicates the left-hand side variable. Arb_{it} measures the frequency of arbitrage opportunities. Arb_{it}^{US} (Arb_{it}^{CA}) measures the frequency of arbitrage opportunities originated because the price of the US share exceeds (is lower than) that of the Canadian share to which it is connected by arbitrage. The right-hand side variables include the volatility index Vix_t, the funding liquidity measure $Noise_t$ developed by Hu, Pan, and Wang (2013), the activity of high-frequency traders in the US (Canada) HFT_{it}^{US} (HFT_{it}^{CA}), and the fraction of short sales marked as "exempt", in compliance with the RegSHO regulation. The results are based on daily measures for 125 Canadian stocks cross-listed in the United States. Standard errors are clustered by stock. Whether time- or stock-fixed effects are included in the specification is indicated in the bottom row. *, **, and *** indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

	(1) Arb_{it}	(2) Arb_{it}	(3) Arb_{it}^{US}	(4) Arb_{it}^{CA}
Vix_t	0.001^{***}			
	(2.704)			
$Noise_t$	0.003^{***}			
	(2.882)			
HFT_{it}^{CA}		-0.162^{***}		
		(-7.441)		
HFT_{it}^{US}		-0.220^{***}		
		(-5.687)		
E/S_{it}			0.017^{***}	-0.019^{***}
			(6.211)	(-8.179)
Adj. R^2	0.257	0.115	0.036	0.058
Observations	30400	30526	29922	29922
F.E.	S	T	T	T

Table III
Correlation of Changes in Prices and Liquidity.

I report the medians and mean stock-day correlations in returns and liquidity changes, in Panels A and B, respectively. I calculate the medians and means separately for two groups of stock-days, based on whether Arb_{it} is below (Low Arb_{it}) or above (High Arb_{it}) its median. I estimate correlations at 15 intraday frequencies. Days with low Arb_{it} corresponds to days when the arbitrageurs are most active. In the "Diff" column I report the differences between the median (mean) correlations for each frequency, together with the statistical significance for its difference from zero, based on a Wilcoxon signed rank (t-) test. *, **, and *** indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Panel A: Correlation in Returns

	Median			Mean		
Time	Low Arb_{it}	High Arb_{it}	Diff	Low Arb_{it}	High Arb_{it}	Diff
1	0.125	0.087	0.038***	0.133	0.107	0.026***
2	0.187	0.136	0.051***	0.194	0.162	0.033***
5	0.300	0.231	0.069***	0.304	0.264	0.040***
10	0.417	0.331	0.087***	0.411	0.366	0.045***
20	0.556	0.454	0.102***	0.526	0.479	0.047***
30	0.643	0.534	0.109***	0.590	0.545	0.046***
60	0.784	0.678	0.106***	0.689	0.653	0.037***
120	0.890	0.814	0.076***	0.770	0.748	0.022***
180	0.929	0.874	0.055***	0.809	0.796	0.013***
240	0.949	0.908	0.041***	0.833	0.825	0.008***
300	0.961	0.927	0.034***	0.850	0.846	0.005**
600	0.980	0.965	0.014***	0.895	0.896	−0.001
1200	0.985	0.978	0.007***	0.926	0.927	−0.002
1800	0.991	0.982	0.009***	0.936	0.938	−0.002
3600	1.000	1.000	0.000***	0.945	0.945	0.001

Panel B: Correlation in Liquidity Changes

	Median			Mean		
Time	Low Arb_{it}	High Arb_{it}	Diff	Low Arb_{it}	High Arb_{it}	Diff
1	0.138	0.040	0.098***	0.152	0.067	0.085***
2	0.148	0.042	0.106***	0.160	0.069	0.091***
5	0.164	0.046	0.118***	0.174	0.074	0.100***
10	0.182	0.051	0.131***	0.191	0.080	0.111***
20	0.205	0.057	0.149***	0.213	0.088	0.126***
30	0.221	0.062	0.159***	0.227	0.093	0.134***
60	0.250	0.071	0.179***	0.253	0.103	0.150***
120	0.281	0.082	0.199***	0.279	0.115	0.164***
180	0.304	0.091	0.213***	0.295	0.122	0.174***
240	0.319	0.100	0.219***	0.307	0.128	0.179***
300	0.330	0.105	0.225***	0.317	0.133	0.184***
600	0.373	0.134	0.240***	0.346	0.152	0.194***
1200	0.422	0.162	0.259***	0.376	0.170	0.206***
1800	0.455	0.191	0.264***	0.391	0.183	0.208***
3600	0.564	0.300	0.264***	0.406	0.202	0.204***

Table IV
Correlation of Changes in Prices and Liquidity Holding Time-Series Effects Fixed

I report the medians and mean stock-day correlations in returns and liquidity changes, in Panels A and B, respectively. I calculate the medians and means separately for two groups of stock-days, based on whether Arb_{it} is below (Low Arb_{it}) or above (High Arb_{it}) its day-specific median. I repeat the analysis at 15 intraday frequencies. Days with low Arb_{it} correspond to days when the arbitrageurs are most active. In the "Diff" column I report the differences between the median (mean) correlations for each frequency, together with the statistical significance for its difference from zero, based on a Wilcoxon signed rank (t-) test. *, **, and *** indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Panel A: Correlation in Returns						
	Median			Mean		
Time	Low Arb_{it}	High Arb_{it}	Diff	Low Arb_{it}	High Arb_{it}	Diff
1	0.125	0.088	0.037***	0.133	0.107	0.025***
2	0.186	0.137	0.050***	0.194	0.162	0.031***
5	0.299	0.232	0.067***	0.303	0.265	0.038***
10	0.416	0.333	0.084***	0.410	0.367	0.043***
20	0.555	0.456	0.099***	0.525	0.480	0.045***
30	0.642	0.536	0.106***	0.590	0.546	0.044***
60	0.782	0.680	0.102***	0.689	0.654	0.035***
120	0.889	0.816	0.073***	0.769	0.749	0.021***
180	0.929	0.876	0.054***	0.808	0.796	0.012***
240	0.949	0.909	0.040***	0.833	0.826	0.007***
300	0.960	0.928	0.032***	0.850	0.846	0.003
600	0.979	0.966	0.013***	0.895	0.897	−0.002
1200	0.985	0.978	0.007***	0.925	0.928	−0.003*
1800	0.991	0.982	0.009***	0.935	0.938	−0.003*
3600	1.000	1.000	0.000***	0.945	0.945	0.000
Panel B: Correlation in Liquidity Changes						
	Median			Mean		
Time	Low Arb_{it}	High Arb_{it}	Diff	Low Arb_{it}	High Arb_{it}	Diff
1	0.139	0.039	0.100***	0.153	0.066	0.087***
2	0.150	0.042	0.108***	0.161	0.069	0.092***
5	0.166	0.045	0.121***	0.175	0.073	0.102***
10	0.184	0.051	0.133***	0.192	0.079	0.114***
20	0.209	0.056	0.152***	0.215	0.086	0.129***
30	0.224	0.061	0.163***	0.230	0.092	0.138***
60	0.253	0.071	0.183***	0.255	0.101	0.154***
120	0.285	0.081	0.204***	0.282	0.113	0.169***
180	0.307	0.090	0.217***	0.298	0.120	0.178***
240	0.323	0.097	0.226***	0.310	0.126	0.184***
300	0.334	0.103	0.231***	0.320	0.131	0.189***
600	0.377	0.133	0.243***	0.349	0.150	0.198***
1200	0.426	0.160	0.266***	0.379	0.167	0.212***
1800	0.461	0.188	0.272***	0.394	0.181	0.213***
3600	0.600	0.300	0.300***	0.409	0.200	0.209***

Table V
Correlation of Changes in Prices and Liquidity Holding Cross-Sectional Effects Fixed

I report the medians and mean stock-day correlations in returns and liquidity changes, in Panel A and B, respectively. I calculate the medians and means separately for two groups of stock-days, based on whether Arb_{it} is below (Low Arb_{it}) or above (High Arb_{it}) its stock-specific median. I repeat the analysis at 15 intraday frequencies. Days with low Arb_{it} correspond to days when the arbitrageurs are most active. Under the "Diff" column I report the differences between the median (mean) correlations for each frequency, together with the statistical significance for its difference from zero, based on a Wilcoxon signed rank (t-) test. *, **, and *** indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Panel A: Correlation in Returns

	Median			Mean		
Time	Low Arb_{it}	High Arb_{it}	Diff	Low Arb_{it}	High Arb_{it}	Diff
1	0.105	0.103	0.002**	0.122	0.118	0.003***
2	0.160	0.157	0.003***	0.180	0.176	0.005***
5	0.265	0.261	0.004*	0.287	0.282	0.005***
10	0.373	0.369	0.004	0.390	0.386	0.004
20	0.504	0.498	0.006	0.503	0.501	0.002
30	0.588	0.581	0.008	0.568	0.567	0.002
60	0.732	0.724	0.008	0.671	0.671	−0.000
120	0.855	0.844	0.011*	0.758	0.760	−0.002
180	0.906	0.898	0.008**	0.801	0.803	−0.002
240	0.932	0.924	0.007***	0.828	0.830	−0.002
300	0.947	0.940	0.007***	0.847	0.849	−0.002
600	0.975	0.971	0.004***	0.895	0.897	−0.002
1200	0.983	0.980	0.002***	0.926	0.927	−0.001
1800	0.984	0.982	0.002***	0.937	0.937	−0.000
3600	1.000	1.000	0.000***	0.946	0.944	0.003*

Panel B: Correlation in Liquidity Changes

	Median			Mean		
Time	Low Arb_{it}	High Arb_{it}	Diff	Low Arb_{it}	High Arb_{it}	Diff
1	0.088	0.079	0.009***	0.113	0.105	0.008***
2	0.093	0.084	0.009***	0.119	0.110	0.008***
5	0.101	0.091	0.010***	0.128	0.120	0.009***
10	0.111	0.100	0.011***	0.140	0.131	0.009***
20	0.125	0.109	0.016***	0.156	0.145	0.012***
30	0.131	0.118	0.013***	0.166	0.154	0.012***
60	0.149	0.133	0.016***	0.184	0.172	0.012***
120	0.168	0.156	0.012***	0.203	0.190	0.013***
180	0.182	0.169	0.013***	0.216	0.201	0.016***
240	0.197	0.183	0.014***	0.225	0.210	0.015***
300	0.207	0.192	0.015***	0.233	0.216	0.017***
600	0.246	0.231	0.016***	0.258	0.240	0.018***
1200	0.297	0.273	0.024***	0.283	0.262	0.020***
1800	0.327	0.309	0.018***	0.294	0.280	0.014***
3600	0.400	0.400	0.000**	0.310	0.298	0.012**

Table VI
Regressions of Liquidity Commonality on Arbitrage Activity

This table shows the results from the regression in Equation 5, determining the effect of the presence of arbitrage opportunities on liquidity commonality. The analysis is based on daily data from January to December 2013 of 125 Canadian stocks cross-listed in the US. The left-hand side variable is the commonality in liquidity measured as $R^2_{BA,it}$, the right-hand side variables include a measure of arbitrage opportunities, Arb_{it}, the bid-ask spread in the US, BA^{US}_{it}, the commonality in high-frequency trading activity, $R^2_{HFT,it}$, a measure of market substitutability, $VolRatio_{it}$, the stock return $r^{\perp}_{it}$ orthogonal to the return of the market $r^{m,US}_{it}$, the VIX index, Vix_t, the ratio of mutual fund ownership to shares outstanding, $Mutual$, and a measure of trading commonality $R^2_{Vol,it}$. Some specifications include time-fixed effects, as indicated by F.E. Standard errors are clustered by stock. Statistical significance at the 10%, 5%, and 1% level is denoted by *, **, and ***, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Arb_{it}	−0.190***	−0.194***	−0.093***	−0.089***	−0.105***	−0.091***	−0.083***	−0.090***	−0.075***	−0.078***
	(−10.054)	(−10.022)	(−5.016)	(−4.859)	(−5.699)	(−5.013)	(−4.765)	(−3.933)	(−3.771)	(−3.874)
BA^{US}_{it}			7.056***	7.544***	7.182***	7.140***	8.434***	7.798***	10.052***	9.886***
			(6.560)	(6.920)	(6.913)	(6.694)	(7.942)	(6.213)	(9.544)	(9.407)
$R^2_{HFT,it}$				0.030***					0.020***	0.021***
				(3.977)					(2.849)	(2.946)
$VolRatio_{it}$					−0.106				−0.065	−0.067
					(−1.472)				(−0.867)	(−0.886)
$r^{US,\perp}_{it}$						0.062			0.098	0.113
						(0.210)			(0.362)	(0.413)
$r^{m,US}_{t}$						−0.159			−0.097	
						(−0.222)			(−0.126)	
Vix_t						0.009***			0.011***	
						(2.702)			(3.625)	
$Mutual_{it}$							0.217**		0.264***	0.275***
							(2.083)		(2.670)	(2.782)
$R^2_{Vol,it}$								0.036***	0.032***	0.030***
								(3.191)	(2.958)	(2.718)
Adj. R^2	0.045	0.054	0.089	0.092	0.091	0.082	0.097	0.089	0.098	0.105
Observations	28074	28074	28074	27620	27909	28066	25083	25869	22939	22939
F.E.		T	T	T	T		T	T		T

Table VII
Regressions of Liquidity Commonality on Arbitrage Activity: Log-Transform

This table shows the results from the regression in Equation 5, determining the effect of the presence of arbitrage opportunities on liquidity commonality, using the log-transform for the two main variables of interest, $R^2_{BA,it}$ and Arb_{it}. The analysis is based on daily data from January to December 2013 of 125 Canadian stocks cross-listed in the US. The left-hand side variable is the log of the commonality in liquidity measured as $R^2_{BA,it}$, the right-hand side variables include the log of a measure of arbitrage opportunities, Arb_{it}, the bid-ask spread in the US BA^{US}_{it}, the commonality in high-frequency trading activity $R^2_{HFT,it}$, a measure of market substitability $VolRatio_{it}$, the stock return $r^{\perp}_{it}$ orthogonal to the return of the market $r^{m,US}_{it}$, the VIX index, Vix_t, the ratio of mutual fund ownership to shares outstanding, $Mutual$, and a measure of trading commonality. $R^2_{Vol,it}$. Some specifications include time-fixed effects, as indicated by F.E. Standard errors are clustered by stock. Statistical significance at the 10%, 5%, and 1% level is denoted by *, **, and ***, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$Log(Arb_{it})$	-0.182^{***}	-0.186^{***}	-0.089^{***}	-0.085^{***}	-0.101^{***}	-0.087^{***}	-0.083^{***}	-0.086^{***}	-0.078^{***}	-0.080^{***}
	(−10.640)	(−10.610)	(−5.248)	(−5.051)	(−5.926)	(−5.244)	(−5.093)	(−4.064)	(−4.172)	(−4.218)
BA^{US}_{it}			16.320^{***}	17.525^{***}	16.583^{***}	16.528^{***}	19.424^{***}	18.352^{***}	23.788^{***}	23.412^{***}
			(6.479)	(6.856)	(6.811)	(6.595)	(7.475)	(6.036)	(8.624)	(8.490)
$R^2_{HFT,it}$				0.071^{***}					0.054^{***}	0.056^{***}
				(3.787)					(3.045)	(3.192)
$VolRatio_{it}$					−0.267				−0.163	−0.165
					(−1.593)				(−0.910)	(−0.916)
$r^{US,\perp}_{it}$						0.166			0.343	0.360
						(0.228)			(0.438)	(0.482)
$r^{m,US}_{t}$						0.357			0.494	
						(0.175)			(0.219)	
Vix_t						0.022^{***}			0.029^{***}	
						(2.677)			(3.587)	
$Mutual_{it}$							0.350		0.434^{*}	0.462^{*}
							(1.358)		(1.740)	(1.861)
$R^2_{Vol,it}$								0.061^{**}	0.051^{*}	0.045
								(2.107)	(1.784)	(1.571)
Adj. R^2	0.035	0.041	0.065	0.067	0.067	0.060	0.071	0.064	0.071	0.076
Observations	28074	28074	28074	27620	27909	28066	25083	25869	22939	22939
F.E.		T	T	T	T		T	T		T

Table VIII
Regressions of Liquidity Commonality on Arbitrage Activity: Alternative Arbitrage Measures

This table shows the results from the regression in Equation 5, determining the robustness of my findings to alternative specifications of the arbitrage opportunity measure. The analysis is based on daily data from January to December 2013 of 125 Canadian stocks cross-listed in the US. The left-hand side variable is the commonality in liquidity measured as $R^2_{BA,it}$. The right-hand side variables include several measures of arbitrage opportunities, the frequency of arbitrage opportunities larger than a basis point, $Arb1bp_{it}$, their maximum relative size $MaxRelArb_{it}$ (in basis points), their relative size $RelArb_{it}$ (in basis points), average $Duration_{it}$ (in seconds) and a measure of the half-life of pricing shocks. All measures are defined in detail in Subsection IV.A. Other right-hand side variables include the bid-ask spread in the US, BA^{US}_{it}, the commonality in high-frequency trading activity, $R^2_{HFT,it}$, a measure of market substitutability, $VolRatio_{it}$, the stock return $r^{\perp}_{it}$ orthogonal to the return of the market $r^{m,US}_{it}$, the VIX index, Vix_t, the ratio of mutual fund ownership to shares outstanding, $Mutual$, and a measure of trading commonality $R^2_{Vol,it}$. Standard errors are clustered by stock. Statistical significance at the 10%, 5%, and 1% level is denoted by *, **, and ***, respectively.

	(1)	(2)	(3)	(4)	(5)
$Arb1bp_{it}$	−0.034***				
	(−4.298)				
$MaxRelArb_{it}$		−0.012***			
		(−3.749)			
$RelArb_{it}$			−0.015***		
			(−4.202)		
$Duration_{it}$				−0.076**	
				(−2.319)	
$HalfLife_{it}$					−0.051**
					(−2.277)
BA^{US}_{it}	10.058***	10.803***	10.383***	11.316***	11.382***
	(9.702)	(10.506)	(10.122)	(11.001)	(11.561)
$R^2_{HFT,it}$	0.020***	0.021***	0.020***	0.021***	0.019***
	(2.838)	(2.953)	(2.884)	(3.091)	(2.731)
$VolRatio_{it}$	−0.050	−0.047	−0.053	−0.026	0.010
	(−0.674)	(−0.614)	(−0.700)	(−0.340)	(0.131)
$r^{US,\perp}_{it}$	0.113	0.064	0.085	0.062	0.014
	(0.421)	(0.237)	(0.313)	(0.227)	(0.052)
$r^{m,US}_{t}$	−0.092	−0.288	−0.194	−0.306	−0.319
	(−0.118)	(−0.373)	(−0.251)	(−0.383)	(−0.412)
Vix_t	0.012***	0.010***	0.011***	0.008***	0.007**
	(3.866)	(3.232)	(3.441)	(2.740)	(2.153)
$Mutual_{it}$	0.267***	0.269***	0.265***	0.237**	0.198*
	(2.712)	(2.671)	(2.663)	(2.364)	(1.887)
$R^2_{Vol,it}$	0.031***	0.030***	0.029***	0.032***	0.033***
	(2.903)	(2.807)	(2.750)	(2.958)	(3.025)
Adj. R^2	0.098	0.096	0.098	0.090	0.098
Observations	22939	22939	22939	22036	22939

Table IX
Regressions of Liquidity Commonality on Arbitrage Activity: Alternative Liquidity Commonality Measures

This table shows the results from the regression in Equation 5, determining the robustness of my findings to alternative specifications of the commonality in liquidity measure. The analysis is based on daily data from January to December 2013 of 125 Canadian stocks cross-listed in the US. The left-hand side variables are indicated in the top row and consist of the commonality in liquidity for the relative, effective, and realized bid-ask spread, in Specification 1 to 3, respectively. The left-hand side in Specification 4 is the commonality in liquidity based on the Amihud measure. The right-hand side variables include a measure of arbitrage opportunities, Arb_{it}, the bid-ask spread in the US, BA_{it}^{US}, the commonality in high-frequency trading activity, $R^2_{HFT,it}$, a measure of market substitutability, $VolRatio_{it}$, the stock return $r_{it}^{\perp}$ orthogonal to the return of the market $r_{it}^{m,US}$, the VIX index, Vix_t, the ratio of mutual fund ownership to shares outstanding, $Mutual$, and a measure of trading commonality $R^2_{Vol,it}$. Standard errors are clustered by stock. Statistical significance at the 10%, 5%, and 1% level is denoted by *, **, and ***, respectively.

	$R^2_{RelBA,it}$	$R^2_{EffBA,it}$	$R^2_{ReaBA,it}$	$R^2_{Amihud,it}$
Arb_{it}	-0.072^{***}	-0.086^{***}	-0.128^{***}	-0.083^{***}
	(−3.547)	(−4.928)	(−4.137)	(−3.219)
BA_{it}^{US}	9.707^{***}	2.515^{**}	4.375^{**}	0.468
	(9.772)	(2.291)	(2.490)	(0.366)
$R^2_{HFT,it}$	0.018^{**}	0.011	−0.006	-0.026^{***}
	(2.525)	(1.575)	(−0.566)	(−2.947)
$VolRatio_{it}$	−0.074	−0.078	0.557^{***}	0.195^{***}
	(−0.994)	(−1.270)	(6.284)	(2.849)
$r_{it}^{US,\perp}$	0.181	0.210	0.232	0.243
	(0.701)	(0.401)	(0.414)	(0.487)
$r_t^{m,US}$	−0.770	0.631	−0.279	-1.889^{*}
	(−1.162)	(0.677)	(−0.204)	(−1.690)
Vix_t	0.009^{***}	0.005	−0.002	0.002
	(2.931)	(1.523)	(−0.319)	(0.550)
$Mutual_{it}$	0.363^{***}	-0.262^{***}	-0.755^{***}	-0.265^{**}
	(3.735)	(−3.118)	(−5.537)	(−2.567)
$R^2_{Vol,it}$	0.034^{***}	0.142^{***}	0.139^{***}	0.159^{***}
	(3.226)	(9.370)	(5.443)	(9.650)
Adj. R^2	0.087	0.032	0.043	0.019
Observations	25087	24948	24945	24308

Table X
Regressions of Liquidity Commonality on Arbitrage Activity: Stock Fixed Effects and Alternative Arbitrage Measures

This table shows the results from the regression in Equation 5, determining the robustness of my findings to alternative regression specifications. The analysis is based on daily data from January to December 2013 of 125 Canadian stocks cross-listed in the US. The left-hand side variable is the commonality in liquidity measured as $R^2_{BA,it}$. The right-hand side variables include several measures of arbitrage opportunities, the frequency of arbitrage opportunities, Arb_{it}, the frequency of arbitrage opportunities larger than a basis point, $Arb1bp_{it}$, their maximum relative size $MaxRelArb_{it}$ (in basis points), their relative size $RelArb_{it}$ (in basis points), average $Duration_{it}$ (in seconds) and a measure of the half-life of pricing shocks. All measures are defined in detail in Subsection IV.A. Other right-hand side variables include the bid-ask spread in the US, BA^{US}_{it}, the commonality in high-frequency trading activity, $R^2_{HFT,it}$, a measure of market substitutability, $VolRatio_{it}$, the stock return $r^{\perp}_{it}$ orthogonal to the return of the market $r^{m,US}_{it}$, the VIX index, Vix_t, the ratio of mutual fund ownership to shares outstanding, $Mutual$, and a measure of trading commonality $R^2_{Vol,it}$. Standard errors are clustered by stock. All specifications include time- and stock-fixed effects. Statistical significance at the 10%, 5%, and 1% level is denoted by *, **, and ***, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
Arb_{it}	−0.010					
	(−0.818)					
$Arb1bp_{it}$		−0.008*				
		(−1.914)				
$MaxRelArb_{it}$			−0.004**			
			(−2.486)			
$RelArb_{it}$				−0.004**		
				(−2.174)		
$Duration_{it}$					−0.033**	
					(−2.020)	
$HalfLife_{it}$						−0.216***
						(−7.781)
BA^{US}_{it}	4.248***	4.132***	4.189***	4.129***	4.091**	4.609***
	(2.666)	(2.639)	(2.676)	(2.624)	(2.514)	(3.385)
$R^2_{HFT,it}$	0.002	0.002	0.002	0.002	0.002	0.001
	(0.386)	(0.374)	(0.377)	(0.368)	(0.381)	(0.128)
$VolRatio_{it}$	−0.009	−0.012	−0.009	−0.011	−0.016	−0.044
	(−0.256)	(−0.334)	(−0.260)	(−0.316)	(−0.463)	(−1.333)
$r^{US,\perp}_{it}$	0.031	0.037	0.035	0.038	0.002	−0.028
	(0.116)	(0.139)	(0.131)	(0.140)	(0.008)	(−0.103)
$Mutual_{it}$	−0.094	−0.096	−0.096	−0.096	−0.124	−0.250
	(−0.454)	(−0.465)	(−0.464)	(−0.465)	(−0.586)	(−1.231)
$R^2_{Vol,it}$	0.005	0.004	0.004	0.004	0.006	0.003
	(0.738)	(0.702)	(0.640)	(0.648)	(0.910)	(0.404)
Adj. R^2	0.217	0.218	0.218	0.218	0.209	0.225
Observations	22939	22939	22939	22939	22036	22939
F.E.	TS	TS	TS	TS	TS	TS

Table XI
Regressions of Liquidity Commonality on Arbitrage Activity: Lagged Independent Variables

This table shows the results from the regression in Equation 5, determining the robustness of my findings to alternative regression specifications. The analysis is based on daily data from January to December 2013 of 125 Canadian stocks cross-listed in the US. The left-hand side variable is the commonality in liquidity measured as $R^2_{BA,it}$. The right-hand side variables include the lagged dependent variable, $R^2_{BA,i,t-1}$, and several measures of arbitrage opportunities, the frequency of arbitrage opportunities, Arb_{it}, the frequency of arbitrage opportunities larger than a basis point, $Arb1bp_{it}$, their maximum relative size $MaxRelArb_{it}$ (in basis points), their relative size $RelArb_{it}$ (in basis points), average $Duration_{it}$ (in seconds) and a measure of the half-life of pricing shocks. All measures are defined in details in Subsection IV.A. Other right-hand side variables include the bid-ask spread in the US, BA^{US}_{it}, the commonality in high-frequency trading activity, $R^2_{HFT,it}$, a measure of market substitutability, $VolRatio_{it}$, the stock return $r^{\perp}_{it}$ orthogonal to the return of the market $r^{m,US}_{it}$, the VIX index, Vix_t, the ratio of mutual fund ownership to shares outstanding, $Mutual$, and a measure of trading commonality $R^2_{Vol,it}$. All independent variables are lagged by one period. Standard errors are clustered by stock. Statistical significance at the 10%, 5%, and 1% level is denoted by *, **, and ***, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
$Arb_{i,t-1}$	-0.073^{***}					
	(-5.189)					
$Arb1bp_{i,t-1}$		-0.030^{***}				
		(-5.176)				
$MaxRelArb_{i,t-1}$			-0.012^{***}			
			(-5.546)			
$RelArb_{i,t-1}$				-0.014^{***}		
				(-5.913)		
$Duration_{i,t-1}$					-0.065^{**}	
					(-2.300)	
$HalfLife_{i,t-1}$						-0.026
						(-1.397)
$R^2_{BA,i,t-1}$	0.197^{***}	0.196^{***}	0.198^{***}	0.197^{***}	0.195^{***}	0.199^{***}
	(13.396)	(13.356)	(13.199)	(13.342)	(13.382)	(13.146)
$BA^{US}_{i,t-1}$	7.202^{***}	7.334^{***}	7.886^{***}	7.529^{***}	8.323^{***}	8.520^{***}
	(8.846)	(8.961)	(9.742)	(9.329)	(9.801)	(11.102)
$R^2_{HFT,i,t-1}$	0.010	0.010	0.011	0.010	0.008	0.010
	(1.358)	(1.371)	(1.500)	(1.418)	(1.165)	(1.391)
$VolRatio_{i,t-1}$	-0.054	-0.038	-0.037	-0.043	-0.014	-0.001
	(-0.920)	(-0.652)	(-0.616)	(-0.711)	(-0.236)	(-0.024)
$r^{US,\perp}_{i,t-1}$	0.344	0.351	0.311	0.332	0.267	0.272
	(1.219)	(1.265)	(1.079)	(1.163)	(0.903)	(0.949)
$Mutual_{i,t-1}$	0.232^{***}	0.234^{***}	0.237^{***}	0.234^{***}	0.220^{**}	0.193^{**}
	(2.836)	(2.861)	(2.832)	(2.821)	(2.583)	(2.209)
$R^2_{Vol,i,t-1}$	0.030^{***}	0.030^{***}	0.028^{***}	0.028^{***}	0.028^{***}	0.032^{***}
	(3.329)	(3.294)	(3.099)	(3.079)	(3.124)	(3.501)
Adj. R^2	0.139	0.139	0.138	0.139	0.130	0.137
Observations	21869	21869	21869	21869	20978	21869
F.E.	T	T	T	T	T	T

Table XII
Liquidity Commonality and Arbitrage Activity: The Bond and Stock Market

This table shows the results from regressing the relative bid-ask spread for stock i in month m, $RelBA_{im}$, on the average imputed round-trip cost of the bonds issued by the company, IRC_{im}, a measure of the arbitrage opportunities between stock and bonds, κ_{im}, the yield of a 3-month government bond, $Tbill_m$, the VIX index, Vix_m, and interactions between the variables. The sample consists of all bond-stock pairs available from 2012 to 2015, for which data on stock prices, credit default swap spreads, and bond trading are available. Specification 3 includes time-fixed effects. Standard errors are clustered by stock. Statistical significance at the 10%, 5%, and 1% level is denoted by *, **, and ***, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
IRC_{im}	0.052^{***}	0.089^{***}	0.089^{***}	0.036^{***}	0.031	0.064^{**}
	(4.500)	(4.041)	(4.143)	(3.272)	(1.291)	(2.158)
κ_{im}		0.000	0.000			0.000
		(−0.633)	(−0.527)			(−0.591)
$\kappa_{im} \cdot IRC_{im}$		-0.103^{***}	-0.108^{***}			-0.107^{***}
		(−2.741)	(−2.898)			(−2.917)
$Tbill_m$				0.001^{**}		0.001^{**}
				(2.270)		(2.129)
$Tbill_m \cdot IRC_{im}$				0.258		0.273
				(1.449)		(1.563)
Vix_m					0.000^{*}	0.000
					(1.673)	(1.205)
$Vix_m \cdot IRC_{im}$					0.001	0.001
					(0.751)	(0.396)
Adj. R^2	0.058	0.074	0.089	0.067	0.061	0.085
Observations	2686	2682	2682	2686	2686	2682

Table XIII
Quote Combinations Faced by the Arbitrageur

This table shows all possible realization of the bid- and ask-quotes on the two markets in the simple trading model. The bid price in market 1 is $B_1 = \alpha + \varepsilon_1$ where ε_1 takes the value of -0.01, 0, or 0.01 with equal probability $\frac{1}{3}$. The ask-price is given by $A_1 = B_1 + \mu_1$ where μ_1 is equal to 0.01 or 0.02, with equal probability $\frac{1}{2}$. Similarly $B_2 = \alpha + \varepsilon_2$ and $A_2 = B_2 + \mu_2$ where ε_2 and μ_2 are independent and identically distributed to ε_1 and μ_1, respectively. In this table, $\alpha = 98$. The realizations of the variables are indicated in the top rows and left-most columns. The side of the market is indicated in the third row and the market is indicated in the third column. Quote combinations highlighted in red represent crossed quotes, while quote combinations highlighted in grey represent overlapping quotes.

			$\varepsilon_2 = -0.01$				$\varepsilon_2 = 0.00$				$\varepsilon_2 = 0.01$			
			$\mu_2 = 0.01$		$\mu_2 = 0.02$		$\mu_2 = 0.01$		$\mu_2 = 0.02$		$\mu_2 = 0.01$		$\mu_2 = 0.02$	
			B	A	B	A	B	A	B	A	B	A	B	A
$\varepsilon_1 = -0.01$	$\mu_1 = 0.01$	1	97,99	98,00	97,99	98,00	97,99	98,00	97,99	98,00	97,99	98,00	97,99	98,00
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03
	$\mu_1 = 0.02$	1	97,99	98,01	97,99	98,01	97,99	98,01	97,99	98,01	97,99	98,01	97,99	98,01
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03
$\varepsilon_1 = 0.00$	$\mu_1 = 0.01$	1	98,00	98,01	98,00	98,01	98,00	98,01	98,00	98,01	98,00	98,01	98,00	98,01
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03
	$\mu_1 = 0.02$	1	98,00	98,02	98,00	98,02	98,00	98,02	98,00	98,02	98,00	98,02	98,00	98,02
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03
$\varepsilon_1 = 0.01$	$\mu_1 = 0.01$	1	98,01	98,02	98,01	98,02	98,01	98,02	98,01	98,02	98,01	98,02	98,01	98,02
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03
	$\mu_1 = 0.02$	1	98,01	98,03	98,01	98,03	98,01	98,03	98,01	98,03	98,01	98,03	98,01	98,03
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03

Table XIV
Quote Combinations Faced by the Arbitrageur

This table shows all possible realization of the bid- and ask-quotes on the two markets in the simple trading model, after the arbitrageur submits her market orders. The bid price in market 1 is $B_1 = \alpha + \varepsilon_1$ where ε_1 takes the value of -0.01, 0, or 0.01 with equal probability $\frac{1}{3}$. The ask-price is given by $A_1 = B_1 + \mu_1$ where μ_1 is equal to 0.01 or 0.02, with equal probability $\frac{1}{2}$. Similary $B_2 = \alpha + \varepsilon_2$ and $A_2 = B_2 + \mu_2$ where ε_2 and μ_2 are independent and identically distributed to ε_1 and μ_1, respectively. In this table, $\alpha = 98$. The realizations of the variables are indicated in the top rows and left-most columns. The side of the market is indicated in the third row and the market is indicated in the third column.Quote combinations highlighted in red represent crossed quotes, while quote combinations highlighted in grey represent overlapping quotes.

			$\varepsilon_2 = -0.01$				$\varepsilon_2 = 0.00$				$\varepsilon_2 = 0.01$			
			$\mu_2 = 0.01$		$\mu_2 = 0.02$		$\mu_2 = 0.01$		$\mu_2 = 0.02$		$\mu_2 = 0.01$		$\mu_2 = 0.02$	
			B	A	B	A	B	A	B	A	B	A	B	A
$\varepsilon_1 = -0.01$	$\mu_1 = 0.01$	1	97,99	98,00	97,99	98,00	97,99	98,00	97,99	98,00	97,99	98,01	97,99	98,01
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,00	98,02	98,00	98,03
	$\mu_1 = 0.02$	1	97,99	98,01	97,99	98,01	97,99	98,01	97,99	98,01	97,99	98,01	97,99	98,01
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03
$\varepsilon_1 = 0.00$	$\mu_1 = 0.01$	1	98,00	98,01	98,00	98,01	98,00	98,01	98,00	98,01	98,00	98,01	98,00	98,01
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03
	$\mu_1 = 0.02$	1	98,00	98,02	98,00	98,02	98,00	98,02	98,00	98,02	98,00	98,02	98,00	98,02
		2	97,99	98,00	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03
$\varepsilon_1 = 0.01$	$\mu_1 = 0.01$	1	98,00	98,02	98,01	98,02	98,01	98,02	98,01	98,02	98,01	98,02	98,01	98,02
		2	97,99	98,01	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03
	$\mu_1 = 0.02$	1	98,00	98,03	98,01	98,03	98,01	98,03	98,01	98,03	98,01	98,03	98,01	98,03
		2	97,99	98,01	97,99	98,01	98,00	98,01	98,00	98,02	98,01	98,02	98,01	98,03

Table XV
Regressions of Liquidity Commonality on Arbitrage Measures

Using a set of Canadian stocks cross-listed in the US, I regress Arb_{it}^{US} (Arb_{it}^{CA}), the frequencies of arbitrage opportunities originated because the price of the US stock exceeds (is lower than) its Canadian counterpart, on the fraction of short sales that are classified as "short exempt" and report the parameter in Panel A (B). I estimate the regression for different sub-samples, after dividing the observations in stock-specific quartile, based on the signed trade volume in the two markets, thus obtaining 16 groups of observations. That is, I replicate Specifications 3 and 4 of Table II after dividing the observations in 16 groups, based on the signed volume traded in the Canadian and US market. Standard errors are clustered by stock. Statistical significance at the 10%, 5%, and 1% level is denoted by *, **, and ***, respectively.

Panel A: Specification 3 of Table II					
LHS	Rank Vol_{it}^{CA}	Vol_{it}^{US} Ranks 1	2	3	4
Arb_{it}^{US}	1	0.030^{***}	0.020^{***}	0.016^{***}	0.030^{***}
Arb_{it}^{US}	2	0.024^{***}	0.016^{***}	0.018^{***}	0.014^{***}
Arb_{it}^{US}	3	0.028^{***}	0.016^{***}	0.019^{***}	0.026^{***}
Arb_{it}^{US}	4	0.027^{***}	0.024^{***}	0.007	0.039^{***}

Panel B: Specification 4 of Table II					
LHS	Rank Vol_{it}^{CA}	Vol_{it}^{US} Ranks 1	2	3	4
Arb_{it}^{CA}	1	-0.024^{***}	-0.031^{***}	-0.032^{***}	-0.038^{***}
Arb_{it}^{CA}	2	-0.025^{***}	-0.020^{***}	-0.023^{***}	-0.017^{***}
Arb_{it}^{CA}	3	-0.017^{***}	-0.015^{***}	-0.017^{***}	-0.024^{***}
Arb_{it}^{CA}	4	-0.025^{***}	-0.026^{***}	-0.010^{***}	-0.019^{***}

Table XVI
Short Exempt and Arbitrage

This table presents the empirical estimates of the distributions of the joint and conditional probabilities that a short trade, a "short exempt" trade, or an arbitrage opportunity take place. The table reports the mean, standard deviation, 25th percentile, median, and 75th percentile of the daily probabilities. The observations have a daily frequency and the sample consists of 247 trading days from 2013 for stocks that were cross-listed between Canada and the United States. The "Difference" variable corresponds to $\Pr\left[E_{its} = 1 \mid Arb_{its}^{US} = 1, S_{its} = 1\right] - \Pr\left[E_{its} = 1 \mid S_{its} = 1\right]$.

Variable	Mean	Std	P25	Median	P75
$\Pr\left[E_{its} = 1, Arb_{its}^{US} = 1, S_{its} = 1\right] \cdot 100$	0.0029	0.0017	0.0019	0.0025	0.0034
$\Pr\left[Arb_{its}^{US} = 1, S_{its} = 1\right] \cdot 100$	0.0091	0.0061	0.0061	0.0079	0.0103
$\Pr\left[E_{its} = 1, S_{its} = 1\right] \cdot 100$	0.0748	0.0328	0.0521	0.0679	0.0920
$\Pr\left[S_{its} = 1\right] \cdot 100$	0.4370	0.1026	0.3700	0.4219	0.4878
$\Pr\left[E_{its} = 1 \mid Arb_{its}^{US} = 1, S_{its} = 1\right]$	0.3281	0.0887	0.2927	0.3430	0.3842
$\Pr\left[E_{its} = 1 \mid S_{its} = 1\right]$	0.1679	0.0447	0.1434	0.1681	0.1918
Difference	0.1602	0.0722	0.1208	0.1624	0.2052

Table XVII
Comparison Between Data Transformations

This table reports descriptive statistics for residuals obtained with different transformation of the $R^2_{BA,it}$ and Arb_{it} variables, when the former is regressed on the latter. The residuals are obtained from the regression where I employ the Box-Cox, log-, and logistic-transformation. I report the first, fifth, 25th, 75th, 95th, and 99th percentile of the residual distribution, together with their skewness and kurtosis. I report the same quantities for a standard normal, for comparison.

Estimation	P1	P5	P25	Median	P75	P95	P99	Skewness	Kurtosis
Box-Cox	−2.063	−1.789	−0.760	0.121	0.810	1.446	1.770	−0.304	2.165
Log	−3.237	−2.292	−0.364	0.316	0.675	1.036	1.205	−1.544	5.114
Logistic	−2.887	−2.115	−0.486	0.186	0.676	1.313	1.782	−0.952	3.879
Normal	−2.326	−1.645	−0.674	0.000	0.674	1.645	2.326	0.000	3.000

Table XVIII
Correlation of Changes in Prices and Liquidity.

I report the medians and mean stock-day correlations in returns and liquidity changes, in Panels A and B, respectively. I calculate the medians and means separately for two groups of stock-days, based on whether $Arb_{i,t-1}$ is below (Low Arb_{it}) or above (High Arb_{it}) its median. I estimate correlations at 15 intraday frequencies. Days with low Arb_{it} correspond to days when the arbitrageurs are most active. In the "Diff" column I report the differences between the median (mean) correlations for each frequency, together with the statistical significance for its difference from zero, based on a Wilcoxon signed rank (t-) test. *, **, and *** indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Panel A: Correlation in Returns

	Median			Mean		
Time	Low Arb_{it}	High Arb_{it}	Diff	Low Arb_{it}	High Arb_{it}	Diff
1	0.104	0.103	0.002	0.121	0.119	0.002**
2	0.159	0.157	0.002	0.179	0.177	0.002*
5	0.264	0.262	0.003	0.285	0.283	0.002
10	0.371	0.371	0.001	0.388	0.388	−0.000
20	0.502	0.502	0.000	0.501	0.503	−0.002
30	0.585	0.584	0.000	0.566	0.569	−0.003
60	0.728	0.727	0.001	0.669	0.673	−0.004
120	0.850	0.849	0.001	0.756	0.762	−0.006**
180	0.901	0.903	−0.002	0.799	0.805	−0.007***
240	0.928	0.928	−0.000	0.826	0.832	−0.006***
300	0.943	0.944	−0.001	0.845	0.851	−0.007***
600	0.973	0.973	−0.000	0.893	0.898	−0.005***
1200	0.983	0.983	0.000**	0.924	0.929	−0.005***
1800	0.982	0.982	0.000	0.935	0.938	−0.003**
3600	1.000	1.000	0.000	0.944	0.946	−0.003*

Panel B: Correlation in Liquidity Changes

	Median			Mean		
Time	Low Arb_{it}	High Arb_{it}	Diff	Low Arb_{it}	High Arb_{it}	Diff
1	0.088	0.079	0.010***	0.114	0.105	0.008***
2	0.093	0.083	0.011***	0.119	0.110	0.009***
5	0.102	0.091	0.011***	0.128	0.119	0.009***
10	0.111	0.100	0.012***	0.140	0.131	0.010***
20	0.123	0.111	0.013***	0.156	0.145	0.010***
30	0.132	0.118	0.014***	0.166	0.154	0.012***
60	0.149	0.135	0.014***	0.184	0.172	0.012***
120	0.170	0.153	0.017***	0.204	0.190	0.014***
180	0.184	0.168	0.016***	0.216	0.201	0.015***
240	0.199	0.181	0.017***	0.225	0.210	0.015***
300	0.208	0.191	0.017***	0.232	0.218	0.014***
600	0.250	0.228	0.022***	0.258	0.240	0.018***
1200	0.299	0.270	0.029***	0.282	0.263	0.018***
1800	0.327	0.309	0.018***	0.292	0.281	0.011***
3600	0.400	0.400	0.000**	0.309	0.298	0.011**

Table XIX
Regressions of Liquidity Commonality on Arbitrage Activity: Maker-Taker Fees

This table shows the results from the regression in Equation 5, determining the effect of the presence of arbitrage opportunities on liquidity commonality, using a modified version of the un-transformed Arb_{it}, Arb_{it}^{MTF}. The modified measure accounts for the existence of maker-taker fees, only counting the presence of an arbitrage opportunity if it is higher than 0.006 USD. The analysis is based on daily data from January to December 2013 of 125 Canadian stocks cross-listed in the US. The left-hand side variable is the commonality in liquidity measured $R^2_{BA,it}$, the right-hand side variables include the measure of arbitrage opportunities, Arb_{it}^{MTF}, the bid-ask spread in the US BA_{it}^{US}, the commonality in high-frequency trading activity $R^2_{HFT,it}$, a measure of market substitability $VolRatio_{it}$, the stock return $r_{it}^{\perp}$ orthogonal to the return of the market $r_{it}^{m,US}$, the VIX index, Vix_t, the ratio of mutual fund ownership to shares outstanding, $Mutual$, and a measure of trading commonality, $R^2_{Vol,it}$. Some specifications include time-fixed effects, as indicated by F.E. Standard errors are clustered by stock. Statistical significance at the 10%, 5%, and 1% level is denoted by *, **, and ***, respectively.

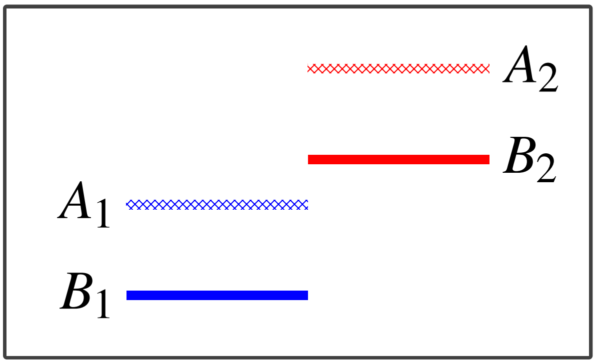
	(1)	(2)	(3)	(4)	(5)	(6)
Arb_{it}^{MTF}	-3.136^{***}	-3.025^{***}				
	(-3.173)	(-2.929)				
$MaxRelArb_{it}^{MTF}$			-19.298^{*}	-26.050^{**}		
			(-1.870)	(-2.331)		
$RelArb_{it}^{MTF}(\cdot 1000)$					-16.825^{***}	-16.578^{***}
					(-2.806)	(-2.698)
BA_{it}^{US}	4.303^{***}	4.260^{***}	4.305^{***}	4.264^{***}	4.305^{***}	4.262^{***}
	(10.647)	(10.457)	(10.699)	(10.513)	(10.703)	(10.506)
$R^2_{HFT,it}$	0.007^{**}	0.007^{**}	0.007^{**}	0.007^{**}	0.007^{**}	0.007^{**}
	(2.402)	(2.443)	(2.368)	(2.385)	(2.365)	(2.408)
$VolRatio_{it}$	-0.012	-0.013	-0.009	-0.010	-0.010	-0.010
	(-0.424)	(-0.434)	(-0.319)	(-0.347)	(-0.331)	(-0.346)
$r_{it}^{US,\perp}$	0.029	0.031	0.015	0.024	0.024	0.028
	(0.270)	(0.281)	(0.136)	(0.216)	(0.222)	(0.250)
$r_t^{m,US}$	-0.085		-0.186		-0.108	
	(-0.295)		(-0.646)		(-0.376)	
Vix_t	0.003^{***}		0.003^{**}		0.003^{**}	
	(2.757)		(2.351)		(2.616)	
$Mutual_{it}$	0.106^{***}	0.109^{***}	0.109^{***}	0.112^{***}	0.105^{**}	0.109^{***}
	(2.624)	(2.704)	(2.678)	(2.748)	(2.591)	(2.667)
$R^2_{Vol,it}$	0.016^{***}	0.015^{***}	0.016^{***}	0.015^{***}	0.015^{***}	0.015^{***}
	(3.924)	(3.667)	(3.927)	(3.674)	(3.916)	(3.658)
Adj. R^2	0.099	0.107	0.097	0.106	0.098	0.106
Observations	22939	22939	22939	22939	22939	22939
F.E.		T		T		T

Figures

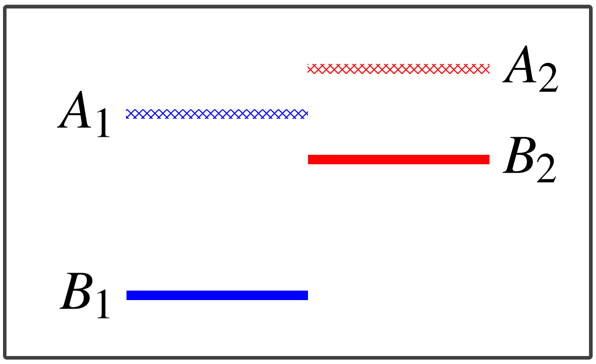
Figure 1
Possible Combinations of Quotes

This figure exemplifies the scenarios that an arbitrageur faces when aiming at profiting from trading in two securities linked by arbitrage trading on market 1 and 2. A_1 and A_2 stand for the ask prices, B_1 and B_2 stand for the bid prices, in market 1 and 2, respectively. Panel A shows crossed quotes, Panel B shows overlapping quotes, Panel C shows included quotes.

A: Crossed Quotes



B: Overlapping Quotes



C: Included Quotes

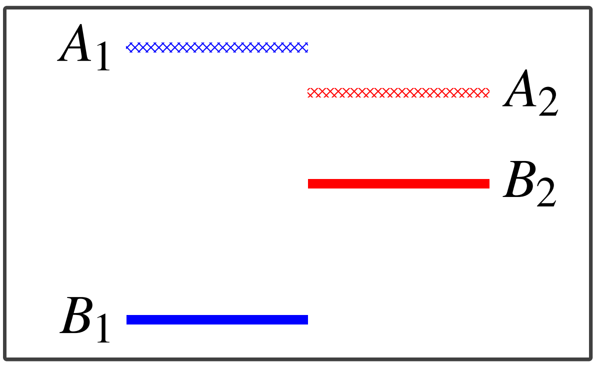
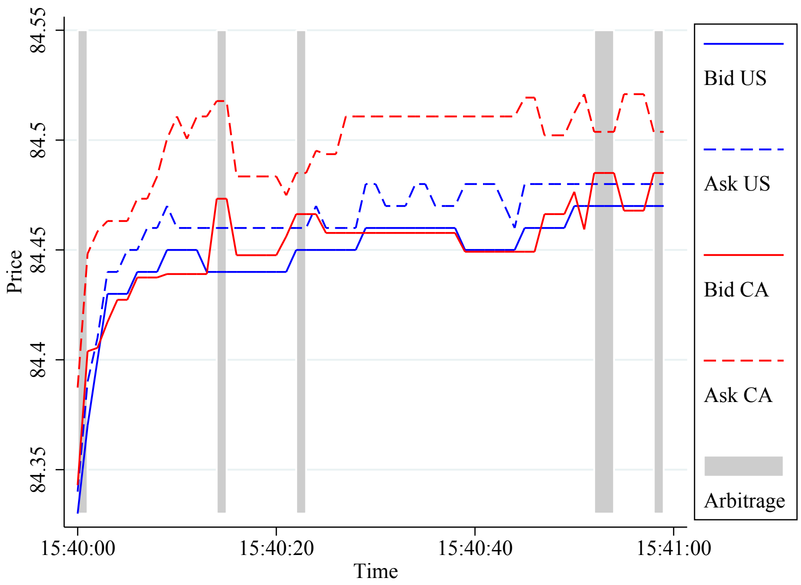


Figure 2
An Example of Arbitrage

This figure shows the prevailing bid- and ask-quotes for a stock of Toronto Dominion on January 2, 2013, between 3:40:00 PM and 3:40:59 PM, on the US stock market and the TSE. Prices for the TSE are shown in US dollars, using the quotes prevailing at the time and have a one-second frequency. Seconds when arbitrage opportunities are present are shaded in gray. Panel A shows the TSE quotes if converted in US dollars using the rights side of the FX quote pair (FX ask for TSE bid and FX bid for TSE ask), while Panel B shows the corresponding quotes if converted into US dollars using the prevailing FX midquote. Stock market data are obtained from the TSE and TAQ, and FX data are obtained from Reuters.

A: Considering FX Liquidity



B: Ignoring FX Liquidity

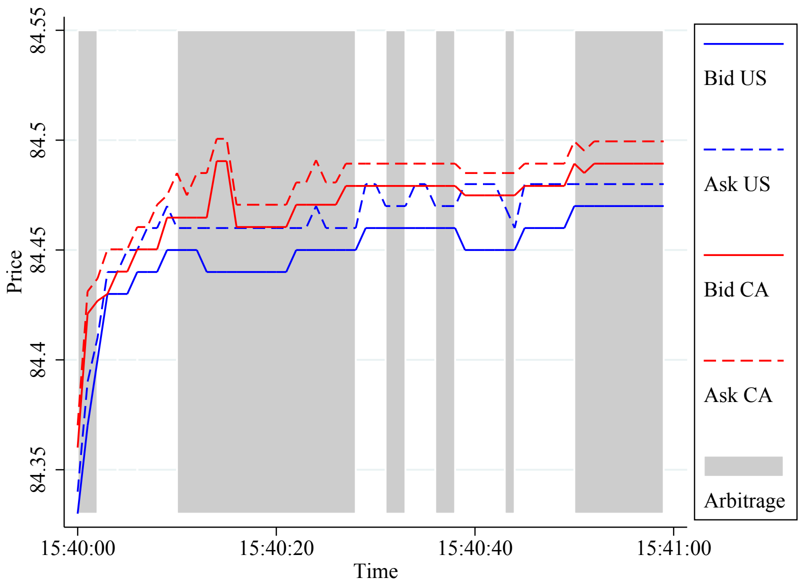
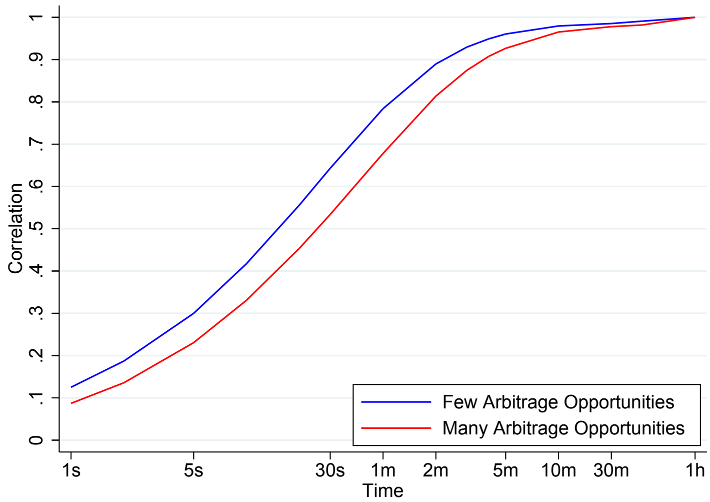


Figure 3
Correlation of Changes in Prices and Liquidity

This figure shows median intraday correlations in returns and liquidity changes between cross-listed securities. The correlations are calculated at different frequencies, from one second to 30 minutes. The medians are evaluated separately for two groups: The stock-days in the sample are divided based on whether Arb_{it} is high or low, i.e., above or below its median. When Arb_{it} is high, many untapped arbitrage opportunities are present on the market, which we interpret as a lack of arbitrage activity. Intraday median correlations from days with substantial (few) arbitrage opportunities are plotted in red (blue). Liquidity is measured as the absolute bid-ask spread. Rank-based correlations are used, consistently, to take into account the discrete nature of the changes in quoted spread. I use data from approximately 30000 observations from 125 Canadian stocks cross-listed in the US.

A: Correlation in Returns



B: Correlation in Liquidity

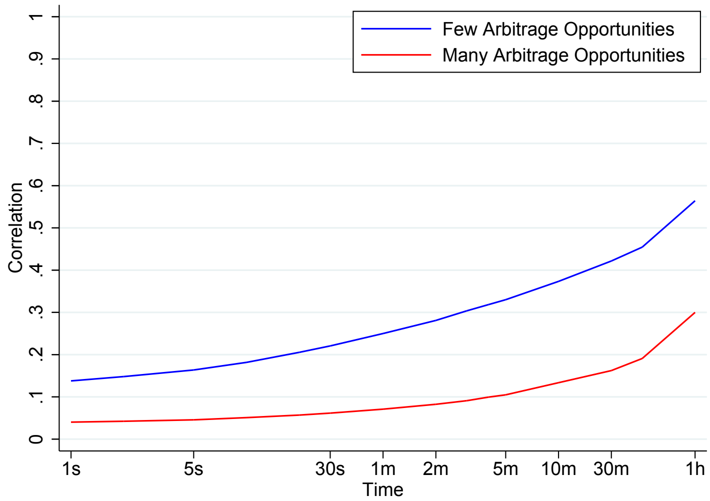
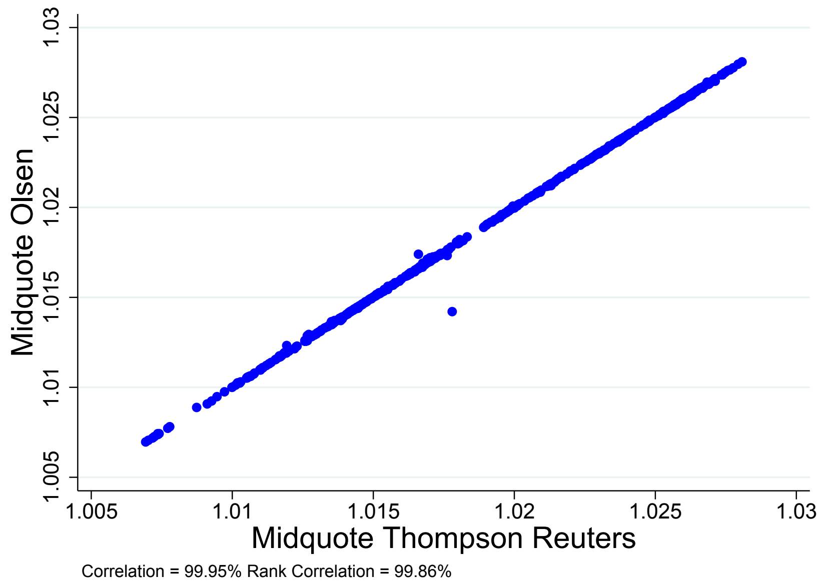


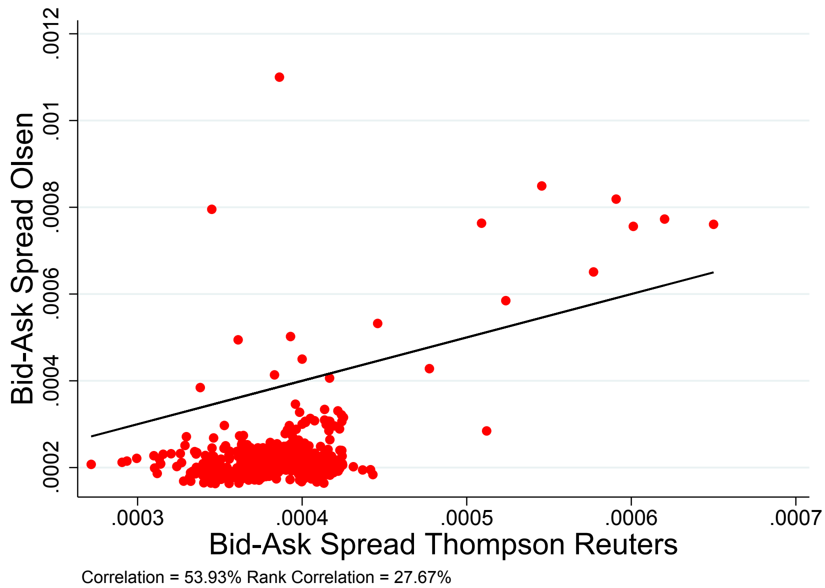
Figure 4
Comparison Between FX Data Sources

This figure shows the comparison between foreign exchange data employed in the empirical analysis, obtained from Thomson Reuters, and data from Olsen Data—a company that consolidates the quotes of multiple FX dealers—for the Canadian–US Dollar currency pair. Millisecond stamped observations between April 1, 2013, and April 30, 2013, are aggregated at a hourly frequency and reported in the graphs. The horizontal axis reports data from Thomson Reuters, while observations from Olsen Data are reported on the vertical axis. Panel A shows the distribution of the midquotes, the average between the bid- and the ask-quotes, while Panel B shows the distribution of the bid-ask spreads, the difference between the ask- and the bid-quote, and the 45-degree line, for ease of comparison. Rank-based and regular correlations between the series are reported in the graphs.

A: Distribution of Midquotes



B: Distribution of Bid-Ask Spreads



Essay 3

Limits to Arbitrage in Sovereign Bonds

with Loriana Pelizzon, Marti G. Subrahmanyam, and Jun Uno

Abstract:

Commonality of liquidity refers to the linkages between liquidity across assets through common market-wide factors, while liquidity discovery refers to the transmission of liquidity between assets linked to each other through arbitrage. In the context of liquidity discovery, the transmission of liquidity shocks between the two assets is supported by the actions of two types of traders: market-makers and arbitrageurs. These two types of players are motivated and constrained by distinctly different forces. This paper investigates the microstructure of the relationship between liquidity discovery, through changes in the quotes posted by market makers and the reactions of arbitrageurs, and price discovery, through the transmission of price shocks between markets.

We use data from the cash and futures markets, at the millisecond level, in the context of the Italian sovereign bond markets during the recent Euro-zone sovereign bond crisis and, surprisingly, find that: (i) even though the futures market leads the cash market in price discovery, the cash market leads the futures market in liquidity discovery, i.e., the willingness of market makers to trade (measured by market depth and bid-ask spread), and (ii) the liquidity in the cash market, and not in the futures market, has a significant impact on the basis between the price of the futures contract and that of the cash bond that is cheapest to deliver. However, the interventions of the European Central Bank (ECB), during the Euro-zone crisis, had a significant effect on the arbitrage mechanism, and hence the lead-lag liquidity relationship between the cash and futures markets.

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I Introduction

The market liquidity of financial assets has deservedly received increasing attention in recent years among academics, practitioners and regulators. It is now well understood that liquidity and liquidity risk are reflected in the prices of financial assets and should be taken into account by investors in their asset allocation decisions. The importance of this issue is reflected in the vast academic literature on this topic covering many classes of assets, stocks, bonds, and derivatives in a variety of countries. Similarly, most practitioners are increasingly employing formal or informal models to incorporate liquidity into their asset allocation decisions. Liquidity is also a central concern of regulators, who now require financial institutions to maintain capital to address the potential illiquidity of their asset portfolios.

Commonality of liquidity refers to the linkages between liquidity across assets through common market-wide factors, while liquidity discovery refers to the transmission of liquidity between assets linked to each other through arbitrage. In the context of liquidity discovery, the transmission of liquidity shocks between the two assets is supported by the actions of two types of players: market-makers and arbitrageurs. This paper investigates the microstructure of the relationship between liquidity discovery, through changes in the quotes posted by market makers and the reactions of arbitrageurs, and price discovery, the transmission of price shocks between markets. Our empirical analysis is in the context of the Italian sovereign bond cash and futures markets, during the recent Euro-zone sovereign bond crisis, based on data provided by the Mercato dei Titoli di Stato (MTS), for the cash bonds, and Reuters, for the futures contracts, at the millisecond level. To our knowledge, ours is the first paper to investigate liquidity discovery between cash and futures assets in high-frequency quote-driven markets, as well as the role of the liquidity linkage between the two markets as one of the key drivers of the limits to arbitrage.

The investigation of the commonality of liquidity and liquidity discovery is particularly relevant given the progressively stronger linkages across markets, due to faster access to information and trade execution, and the degree to which, and speed with which, liquidity is transmitted across markets today. Just as asset returns exhibit co-movement due to their dependence on market-wide risk factors, it is natural to ask whether market liquidity exhibits a similar commonality across asset classes. An aspect of this issue is the extent to which a liquidity shock in one market is transmitted ("spills over") into another. It is important to emphasize that the transmission mechanism could be studied by analyzing the linkages between these asset classes through their statistical relationships, or more fundamentally, through the portfolio flows between them. We focus on the former type of analysis.

The importance of liquidity discovery across assets linked by arbitrage is heightened by the fact that liquidity is provided not only by market makers, but also by arbitrageurs. Liquidity discovery reflects this qualitatively different behavior of market participants, when the prices of the assets are tightly related through an arbitrage condition. For example, stocks and options written on them, bonds and credit default swaps based on them, and cash assets and their corresponding futures contracts, are all cases where the prices of the two assets are connected through arbitrage – if the prices were to deviate too much from the arbitrage condition, traders would take action to bring them back in line. Hence, the liquidity in the two *closely related* markets has to be strongly related, as well. For example, the price of a futures contract is established in relation to the underlying deliverable cash bonds by an arbitrage condition, so that, when the two prices diverge, arbitrageurs profit from taking a long position in the cheaper security and a short position in the more expensive security, thus locking in a riskless return. Through these actions, arbitrageurs ultimately play a role of liquidity supplier in both sides of markets. When a shock, whether due to information or liquidity, affects either the cash or the futures market, arbitrageurs will profit from it, if there is a divergence between the prices in the two markets. The determination of which market reveals the new information first and, consequently, which market adjusts accordingly, resulting in price discovery, is a question that can only be answered empirically. At the same time, the answer will possibly depend on the observation frequency that is selected for the analysis: the higher is the frequency, the greater is the likelihood of a discrepancy. What should be noted in the specific context of sovereign bonds is the role of the central bank in distorting the arbitrage relationship.

We term the phenomenon of the transmission of liquidity between assets linked by arbitrage as liquidity discovery, describing the process by which information is reflected in market *liquidity*, in a manner analogous to the concept of price discovery, which relates to the reflection of information in *prices*. Specifically, if the information shock resulted first in the creation of liquidity in the futures market, we would conclude that liquidity discovery takes place there first. Further, if the cash market liquidity responded quickly to this initial discovery, we would surmise that the lead-lag in the liquidity discovery process between the two markets is modest and the speed of response of arbitrage rapid.

Through the actions of the market makers and the arbitrageurs, the microstructure of the two markets determines the liquidity discovery process, i.e., the adjustment of liquidity in the two markets to the arrival of new information. One possibility is that the adjustment takes place through changes in the quotes posted by market makers: a widening of the quoted bid-ask spread causes large price changes, accentuating the realized volatility, in turn leading to a correlation between price and spread changes. Alternatively, the liquidity adjustment can take place through changes in the quoted quantity (including a zero quoted quantity), instead of just the quotes. Thus, it is possible that the quotes stay the same, but the bid quantity offered declines, due to the risk aversion of the market makers, causing market depth to decline. Hence, liquidity discovery takes on a different dimension in this case: quoted spreads do not change, but changes in quoted quantities may be correlated with the price changes. It should be noted that liquidity is also provided by arbitrageurs in addition to market makers. While market makers engage in passive liquidity provision, subject to the constraints imposed by their market-making obligations, arbitrageurs actively exploit any deviation from the arbitrage condition, subject to their own capital constraints. The analysis of liquidity discovery should, perforce, be influenced by the market-making obligations of the market makers and the limits to arbitrage experienced by the arbitrageurs. These two factors do not necessarily act in the same direction, but may often do so.

In order to investigate the mechanism of liquidity discovery, it is important that both the cash asset and the futures contract based on it are traded directly (rather than being baskets of assets that are traded individually, for example, as in the case of stock indices) in relatively liquid markets. It would also be useful if high-frequency data were available to discern the speed of response of the liquidity in the two markets to an information shock. It would be particularly useful if the markets were exposed to substantial changes in the information available over the period of analysis, since such variation would allow a more granular examination of these liquidity responses. For all these reasons, the Euro-zone sovereign bond markets, and in particular the Italian market, come close to being an ideal laboratory for such an analysis, due to the availability of high-frequency data for both the cash and futures markets. These granular data allow us to determine how the adjustment occurs in the age of algorithmic trading, where market discrepancies are acted on in a matter of minutes, if not seconds. In addition, during the Euro-zone crisis, the market was subject to several information shocks due to market uncertainty as well as the possibility of policy intervention, thus providing enough variation in liquidity discovery and transmission over time, especially when the market was under stress.

It should be emphasized that, to take advantage of the arbitrage opportunity, arbitrageurs need to execute two opposite transactions in the cash and futures markets, virtually simultaneously. Drawing upon the growing literature on commonality in liquidity, we expect the liquidity in the two markets to move together; thus, periods of illiquidity in the cash and futures markets will tend to occur contemporaneously. Arbitrageurs need to take this phenomenon into account, which motivates our aim of testing the relationship between shocks to the two markets' liquidity and identifying their driving forces. Once we have determined what is driving the liquidity in the markets, and whether a liquidity shock will generally hit a specific market first, our goal is to statistically determine whether the illiquidity in the two markets is a limit to arbitrage, thus explaining at least part of the divergence between the two otherwise identical securities, the futures contract and its underlying bond.

The recent intervention by the European Central Bank (ECB) and the individual national banks, as well as actions by the individual national treasuries, will surely have affected the liquidity discovery mechanism, simply due to the scale of their operations. For instance, ECB interventions in the cash market, directly through the Securities Markets Programme (SMP) and Outright Monetary Transactions (OMT), and indirectly through the Long-Term Refinancing Operation (LTRO), may have had different and potentially perverse effects on the limits to arbitrage between these two markets, and hence on their liquidity. For example, in the case of LTRO, the provision of liquidity to the banks by the ECB improved the liquidity transmission between the cash and futures markets and helped close the basis between the two. In contrast, the SMP provided liquidity to one side of the cash market, helped *create* the basis gap between the cash and futures markets, and weakened the liquidity discovery mechanism.

The objective of this paper is to understand the linkage between the cash and futures markets and the effect of a decline in liquidity in either market on the cash-futures relationship for Euro-zone sovereign bonds. An important consideration is to be mindful of the impact of ECB interventions on the linkage between these two markets in terms of price and liquidity. We distinguish between the change in liquidity that comes from a change in the information set available to the investors, and shocks to liquidity that originate from pure liquidity providers, such as the risk-taking stance of market makers and the lending difficulties following intervention by the ECB. We show how liquidity measures captured by price and quote information are related to market makers' activities that we cannot usually observe. Our detailed data, from MTS for the cash market and EUREX for the futures market, allow us to describe the individual market makers' actions in posting quotes and the arbitrage activity of those choosing to exploit the basis between the cash and futures markets.

We show that, even though the futures market leads the cash market in price discovery, the cash market leads the futures market in liquidity discovery, i.e., the willingness of the market makers to trade. More specifically, the liquidity in the cash market also has a significant impact on the changes in the basis between the prices of the futures contract and the cash bond that is cheapest to deliver. This is a novel and surprising result that shows a strong linkage, through the behavior of arbitrageurs, between illiquidity in the cash market and illiquidity in the futures market. Moreover, we show that the driving force behind market liquidity in the cash market (i.e., the willingness of market makers in this market to trade) is also an important factor that statistically determines when the illiquidity in the two markets acts as a limit to arbitrage, thus explaining at least part of the divergence between the two otherwise identical securities, the futures contract and its underlying bond(s). Finally, our investigation of the ECB intervention shows that the introduction of the LTRO program restored liquidity in both the futures and the cash bond market, drove the basis to zero and eliminated the lead-lag relationship between the illiquidity in the cash and future markets, while the SMP did quite the opposite.

The related literature is presented in Section II. The bond and futures market structures and the data are described in Section III. The research methodology is explained in Section IV. The empirical results are presented in Section V and Section VI concludes.

II Related Literature

Our research draws from and contributes to several strands of the literature. First, we shed light on the price discovery between the sovereign bond futures and underlying cash bond markets, in the sense of Garbade and Silber (1983) and Hasbrouck (1995). We analyze this concept and the related concept of arbitrage in the cash-futures relationship in a high-frequency setting. These are issues that have received limited attention, particularly in the context of sovereign bond markets. The previous literature, based largely on a much earlier period, has mainly shown that price discovery and the elimination of arbitrage opportunities takes place over several days (see Brenner, Subrahmanyam, and Uno, 1989, for example). However, with the surge in high-frequency and algorithmic trading in recent years, a more granular analysis is clearly necessary, to match the current technology and architecture of the sovereign bond markets. In this vein, an earlier study can be found in Brandt, Kavajecz, and Underwood (2007), which analyzes the effect of order flow in the bond and futures markets on their respective returns. However, this research does not address the issue of liquidity explicitly.

Second, our study relates to the growing literature on commonality in liquidity. The microstructure literature, as surveyed in O'Hara (1995) and Hasbrouck (2007), primarily focuses on single stock attributes, and generally deals with them as the solution to an optimization problem by the stock's market maker(s). Chordia, Roll, and Subrahmanyam (2000)shift the focus from a single stock to the interaction between stocks; fitting a market model to a liquidity measure, they show that the single stock co-moves with the market-wide average liquidity. Although they find empirical support for this commonality being affected by inventory risk and asymmetry of information, they argue that the reason behind the co-movement is to be found in the prevailing macroeconomic conditions. In a contemporaneous work, Hasbrouck and Seppi (2001) show, in a model-free setting, that the order flows of stocks traded on the NYSE can be explained through a common variation component; however, they only find modest significance for commonality in standard liquidity measures. Similarly to Chordia, Roll, and Subrahmanyam (2000) and Chordia, Sarkar, and Subrahmanyam (2005), Huberman and Halka (2001) document commonality in liquidity, which they attribute to systematic variation over time in the amount of noise traders present.

Brunnermeier and Pedersen (2009) develop a theoretical model capable of explaining commonality in market liquidity via constraints in funding liquidity, i.e., the supply side. Their model predicts that, in times of high volatility or significant market downturn, intermediaries such as market makers are faced with margin requirements and restricted access to funding, which leads them to curtail the provision of liquidity to the market. Coughenour and Saad (2004) find significant empirical support for this prediction, showing that stocks handled by the same market maker co-move with each other, even after controlling for market-wide movements. Other models are closer in spirit to Chordia et al. (2000) and try to identify the source of commonality on the demand side. Koch et al. (2016) show that the correlation between trading by different investors contributes to the commonality; specifically, they show that flow-induced mutual fund trading is an important factor. Karolyi, Lee, and Van Dijk (2012)document the commonality in liquidity in 40 countries, and take advantage of the different legal frameworks to disentangle the demand- and supply-side evidence, finding robust support for the demand-side explanation, while linking commonality to market-specific features. Brockman et al. (2009) also show that within-exchange commonality is present in a cohort of exchanges, and extend the analysis, documenting “across-exchange” co-movement of liquidity, or the existence of a global liquidity commonality. Lee (2011) makes a similar point, arguing that the correlation between a stock’s liquidity and the global and local market returns is priced in the stock’s return.

The issue of commonality in liquidity has been investigated in other markets as well. Marshall et al. (2013) present evidence of liquidity across commodities, arising from the supply-side channel, while their test for commonality between commodities and the stock market fails to reject the null hypothesis of no such relationship. Banti, Phylaktis, and Sarno (2012) and Mancini, Ranaldo, and Wrampelmeyer (2013) document strong commonality in liquidity in the FX market, while Chordia et al. (2005) analyze the liquidity co-movements between the stock and bond markets.

The strand of literature that is most closely related to our paper deals with liquidity-motivated limits to arbitrage and liquidity discovery. Similar to the literature on commonality in liquidity, trading in multiple securities is considered; however, these securities are linked by an arbitrage condition, and market illiquidity is generally identified as a factor limiting the convergence of the securities’ prices and eliminating arbitrage opportunities. Studies by Brenner et al. (1989) and Roll, Schwartz, and Subrahmanyam (2007) are driven by the same motivation as ours, and are worthy of special mention. In particular Roll et al. (2007) investigate the arbitrage opportunities between the futures contract on the NYSE composite index and the underlying stocks, testing whether price discovery is affected by the liquidity of the underlying securities. They find that the speed of price convergence is positively related to the liquidity of the stocks, and that shocks to the basis are informative in predicting liquidity, hence finding a two-way causality between the price discrepancy and the liquidity of the market. However, they do not investigate the liquidity in the futures market, and hence do not investigate liquidity discovery, per se. Furthermore, the individual traded securities they analyze are not *directly* linked to the basis, since the price of the cash stock index in their analysis may well be stale. In addition, they use daily data for their analysis, rather than intra-day data, which may reveal a different pattern for the arbitrage mechanism. More importantly, there is no single player that influences the arbitrage mechanism similarly to the central bank in our context of sovereign bonds.

This broad issue of liquidity discovery has been examined in other markets. In the context of credit default swap (CDS)-bond arbitrage, Fontana (2011), Nashikkar, Subrahmanyam, and Mahanti (2011) and Bai and Collin-Dufresne (2011) show that a high basis can be partially explained by a drying-up of the market liquidity in the bond or CDS. Chan et al. (2008) study American Depository Receipts (ADRs) and provide evidence that an increase in the ADR premium is associated with an increase in the liquidity in the ADR market.

Our study differs from previous studies for several reasons. First, we investigate liquidity discovery during the distressed market periods of the Euro-crisis, especially in the context of intervention by the ECB. Second, we focus on the interaction between the arbitrage opportunities, reflected by the basis and liquidity in the cash and futures markets. Hence, we bridge the two strains of literature, studying arbitrage relations with a focus on market liquidity, which we can do thanks to the high granularity of our data, and by investigating the transmission of liquidity between two securities that have *identical* cashflows and credit risk, focusing on the arbitrage trades and quotes between them. Third, we use detailed intra-day data provided by MTS and Eurex, which allows us to examine order flow, quote setting and market depth, adding more detail to our liquidity measures.

III Data

The data we use in this study are obtained from diverse sources. The data for the cash sovereign bonds traded on the MTS are obtained from the MTS Group. This new and unique dataset consists of detailed quote, order and transaction data for all of the European sovereign bonds in MTS, an interdealer market. The MTS market is fully automated and effectively works as an electronic limit order market. We obtained data for a cohort of 152 Italian sovereign bonds, during the period from June 1, 2011 to December 31, 2012.

The bond futures data, obtained from Reuters, encompass all trades and quotes for futures contracts on long-term coupon-bearing bonds on Eurex, a major stock and futures exchange, owned by the Deutsche Boerse group. Both datasets are time-stamped at the millisecond level and allow us to analyze the dynamics of the high-frequency interaction between the cash and futures markets, which are linked by arbitrage. In addition, we obtained data on contract definitions, including details of the basket of bonds deliverable into the futures contract, from the Eurex website.

To calculate the futures-bond basis, we use daily data on the repo rate obtained from Bloomberg, and information on the bonds' features, including coupon rate and payment schedules, obtained from MTS.

III.A The EUREX Futures Market Structure and Data

Italian government bond futures are traded on the Eurex Exchange, which offers a continuous, electronic trading platform where liquidity is provided by diverse participants who act as market makers. However, there is only one designated market maker in the futures market compared to around 25 designated market makers in the Buoni del Tesoro Poliennali (BTP) cash market. Three futures contracts, based on Italian sovereign bonds, are listed on this exchange: Long-term, Mid-Term, and Short-Term Euro-BTP contracts. The underlying bonds are debt instruments issued by the Republic of Italy. The Long-Term Euro-BTP futures contracts, which were introduced in 2009, are the focus of this study, since they are, by far, the most liquid of these contracts.[1]

[1]The Short- and Mid-Term contracts of Euro-BTP futures were launched in October 2010 and September 2011, respectively.

For the Long-Term Euro-BTP futures contract, the average daily volume (ADV) is 143,000 contracts during our sample period, June 1, 2011 to December 31, 2012, and the average daily number of trades is 4,255. The minimum price change (tick) is expressed as a percentage of the par value, up to two decimal places, and is €0.01 during most of our sample period. The trading hours are 8 AM to 7 PM CET on most business days, and 8 AM to 12:30 PM CET on the last trading day of the contract. The notional value per contract is €100,000 with a coupon of 6%.

The contract terms specify that a delivery obligation arising from a short position on a long-term contract may only be fulfilled by the delivery of coupon-bearing debt securities issued by the Republic of Italy (BTP), with a remaining life of 8.5 to 11 years and an original maturity of no longer than 16 years. The debt securities must have a minimum issue amount of €5 billion and a nominal fixed payment. Starting with the contract month of June 2012, debt securities of the Republic of Italy have to possess a minimum issuance volume of €5 billion no later than 10 exchange days prior to the last trading day of the current front month contract.

The contracts months are on the March, June, September and December cycle, and the delivery day is the tenth calendar day of the month. The last trading day is two exchange days prior to the delivery day of the relevant maturity month.

III.B The MTS Bond Market Structure and Data

The MTS data include trade and quote data for fixed-income securities, mostly those issued by the national treasuries and local governments of twelve Euro-zone countries: Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal, Slovenia and Spain. The MTS system is the largest interdealer market for Euro-denominated government bonds. The time-series data are based on all MTS interdealer markets making up the MTS system, including EuroMTS (the "European market"), EuroCredit MTS and various domestic MTS markets. The MTS interdealer trading system is fully automated and works as a quote-based electronic limit order market. According to the MTS data manual, "EuroMTS is the reference electronic market for Euro benchmark bonds, or bonds with an outstanding value of at least 5 billion Euro."[2]

The dataset we analyze in the present study is, by far, the most complete representation of the Euro-zone sovereign bond market available, and has been released only recently. It covers *all* trades, quotes, and orders that took place on the MTS market between June 1, 2011 and December 31, 2012. Every event is stamped at the millisecond level, and the order IDs permit us to link each order to the trade that was eventually consummated from it. Every quote in this market, henceforth called "proposals," can be followed in the database in terms of their "revisions" over time, thanks to an identifier.

Market participants can decide whether they want to trade a government bond on the European market or on that country's domestic market. While every Euro-zone bond is quoted on the

[2]See also Dufour and Skinner (2004) and Pelizzon, Subrahmanyam, Tomio, and Uno (2016)

domestic markets, only bonds that were issued for an amount higher than a certain threshold can be traded on the EuroMTS. Even though the two markets are not formally linked, most dealers participate in both venues. The previous literature (Cheung, Rindi, and De Jong, 2005, Caporale and Girardi, 2011) has shown that the two markets essentially constitute a single venue.[3] Thus, in our analysis we consider trading in *both* markets.

There are two kinds of trader in the sovereign bond markets, primary dealers and other dealers. Primary dealers are authorized market-making members of the market. That is, they issue standing quotes, which can either be single-sided or double-sided, on the bonds they have been assigned. They indicate the quantity they are willing to trade and the non-negative fraction of that quantity they are willing to "show" to the market. Primary dealers can be on the passive side of the market, when their proposals are hit, and/or on the active side, when they submit orders aimed at hitting another primary dealer's standing quote. Primary dealers have market-making obligations that, in spite of some relaxations after 2007, still require each primary dealer not to diverge from the average quoting times and spreads calculated among all market makers. In this market, the event of crossed quotes is guaranteed not to occur, except by chance, since, when the opposite sides of two proposals cross, a trade takes place for the smaller of the two quoted quantities.[4] Other dealers, with no market-making responsibilities, can originate a trade only by "hitting" or "lifting" the primary dealers' standing quotes with market orders. However, it should be noted that primary dealers are also on the active side of 96% of the trades present in our database.[5]

III.C The Liquidity Measures

In order to measure the liquidity in the futures and cash bond markets, we employ a standard liquidity measure, namely the quoted absolute bid-ask spread.[6] While the bid-ask spread can be calculated for both the futures and the cash bond markets, only the highly detailed level of the MTS dataset provides us with the information to calculate a more comprehensive depth measure, which we analyze in detail below.

The *Quoted Spread* is defined as the difference between the best ask and the best bid, per € 100 of face value, proxying for the cost of immediacy that a trader would face when dealing with a small trade. The depth measure *Lambda* measures by how much a trader would move the best bid (ask) if she were to trade € 15 million of a given bond.[7] Mathematically, the *Lambda* on the

[3]By this we mean that an order could "trade-through" a better price if the trader sent the order to the market with the worse bid- or ask-price. However, MTS assures market participants that their trading platforms always show quotations from both the domestic and the European market, when available.

[4]While this is one way for the primary dealers to trade, it seldom happens. Hence, we do not include trades originating in this manner in our sample.

[5]The MTS dataset does not suffer from the same misreporting issues as other datasets (such as TRACE). However, we apply some data-cleaning procedures to ensure the consistency of the quotes, as detailed in Pelizzon et al. (2013).

[6]We choose to use the absolute and not the relative bid-ask spread in order to avoid incorrectly identifying movements in the mid-quote as movements in the size of the spread.

[7]This amount was chosen since it is the 90th percentile of the overall market in terms of trade size. As traders might

ask side would be defined as $\lambda^A = E\left[(P_t^A - P_{t-1}^A)(Q_t)\,|Q_t = 15M\right] = E\left[\Delta P_t^A(Q_t)\,|Q_t = 15M\right]$, where P_t^A is the time t ask price following a buy trade of quantity $Q_t = 15M$, $and \lambda^B$ would be defined similarly. In order to represent both sides of the market, we consider the mean, $\lambda = \frac{\lambda^A + \lambda^B}{2}$, in our empirical estimations, as a market depth measure.

III.D The Sample Period and Descriptive Statistics of the Databases

The sample period for our study ranges from June 1, 2011 to December 31, 2012. This time period provides a good window in which to study the behavior of European government bond markets during the most recent part of the Euro-zone sovereign debt crisis and the period leading up to it. Specifically, the earlier part of our sample covers a number of significant sovereign events that directly affected the liquidity in Euro-zone government bonds and, in general, the wider loss of confidence in European efforts to manage the sovereign debt crisis. In this period, dealers also witnessed a substantial increase in the Italian bond yield spread (over German Treasury bonds or "Bunds") and Italian sovereign CDS spread. The first few months of great uncertainty culminated in the restoration of market confidence thanks to both the LTRO program, with a three-year maturity, introduced by the ECB in December 2011 and, at the end of July 2012, the speech by Mario Draghi, the ECB President, in which he unveiled the potential for new tools to ease the European sovereign debt crisis.[8] Since Italy has the largest number of bonds traded in the Euro-zone out of the whole sample, with the largest volume, and was the bellwether country during the European sovereign crisis, we initially focus our analysis on Italian government bonds, based on the most detailed historical dataset that MTS makes available to the public.[9]

Table I presents the summary statistics for the various liquidity measures common to both cash and futures markets. Among the quote-based measures, the average bid-ask spread for on-the-run 10-year BTP is 0.307, while that for BTP futures is 0.036%. A comparison of the quoted bid-ask spreads for cash and futures reveals that the BTP futures market has far better liquidity than the cash bond market.

Insert Table I here.

In terms of depth, the average quantity available at the best quotes are €8.35 million for the BTP on-the-run bond, and €7.15 million for the BTP futures that is the depth of the most liquid bond in the BTP cash market is slightly larger than that for the BTP futures contract. This partly reflects the fact that the minimum trading amount for BTP cash bonds is twenty times larger than that for futures contracts (2 million versus 0.1 million).

split up large amounts over several subsequent trades, *Lambda* captures the price movement caused by a relatively large trade requiring immediacy. It is conceptually equivalent to the concept of market depth defined by Kyle (1985).

[8]In his speech on July 26, 2012, at the Global Investment Conference in London, Mario Draghi stated: "The ECB is ready to do whatever it takes to preserve the Euro. And believe me, it will be enough."

[9] In future analysis, we hope to examine the bonds of other Euro-zone countries.

The average number of daily quote revisions of the on-the-run bond and the futures contract are 7597 and 10595, respectively. Intensive quote updates are a common feature of the two instruments. Among the trade-based measures, the average daily number of trades for on-the-run bonds is 23.4, while that for futures it is 3788, which means that there are, on average, 39.5 trades during every five-minute interval during the trading day. Thus, trading activity in the futures market is far greater than that in the interdealer cash bond market. Total volumes in euros are 107.6 and 1288.2, respectively, for the on-the-run bond and the futures contract. The ratio between the on-the-run bond and the futures contract, in terms of the number of transactions, is 1 to 161.8, while in terms of traded volume, it is 1 to 12. This means that the order size of the on-the-run bond is, on average, an order of magnitude larger than that for the futures contract.

Finally, the absolute trade imbalances for the on-the-run bond and the futures contract are 49.7% and 5.7% of the total number of transactions. Again, the cash and futures markets are very different. In the case of on-the-run bonds, a small number of large-sized orders causes a large imbalance between buyer- and seller-initiated orders, while in the case of the futures market many relatively small orders contribute to keeping the order imbalance relatively small. The volume imbalance shows a similar picture. A large imbalance in the BTP cash markets is one of the reasons why the bid-ask spreads there are much larger than in the futures market.

IV Methodology

In a high-frequency trading market, where trading desks positioned next to each other often make markets and try to arbitrage between the cash and futures instruments using algorithms, the dynamics of the price discovery and the transmission of liquidity need to be defined at much shorter intervals than the existing literature has done: in terms of minutes, rather than days. This is possible for us to do, given that high-frequency data have recently been made available for the Euro-zone sovereign bond and futures markets. To uncover the dynamics of this interaction, we investigate price discovery using a cointegration framework, to test whether a zero-basis hypothesis is supported by the data. To address issues relating to limits to arbitrage, we conduct a vector auto-regressive (VAR) analysis of the changes in price and the various liquidity measures, thus eliminating day-, delivery-, and bond-specific disturbances. To draw conclusions about the significance of the dynamic causality between the variables, we use the Wald test, in the spirit of testing for Granger-causality.

More specifically, we investigate three main aspects of the broad issue:

1. Price discovery: Does the futures price lead the cash bond price or vice versa? How does this lead-lag relationship change during periods of crisis, and especially after important policy announcements by the ECB, such as the SMP, OMT or LTRO?

2. Liquidity discovery and spillover: Do shocks to market liquidity spill over into the other market? Is the liquidity of one market driving that of the other?

3. Limits to arbitrage: Is low market liquidity in the cash or futures market an impediment to arbitrageurs who focus on exploiting discrepancies between the prices in the two markets? How does the willingness of the market maker to take the opposite side of a trade in one market affect the market liquidity in the other market, in general?

IV.A Price Discovery

The prices of the futures and the underlying bonds are bound by a tight arbitrage condition as discussed earlier. Hence, in line with the previous literature, we investigate whether the futures market is the one in which new information is first revealed, with the cash market adjusting to this movement with a lag. We investigate this price discovery process using a cointegration framework, allowing the data to indicate the cointegration rank and space, thus statistically testing whether a net-zero-basis hypothesis, predicted by the arbitrage argument, is supported by the data. The model we estimate is as follows:

$$\begin{pmatrix} \Delta P_{cash,t} \\ \Delta P_{Fut,t} \end{pmatrix} = \alpha\beta' \begin{pmatrix} P_{cash,t-1} \\ P_{Fut,t-1} \\ 1 \end{pmatrix} + \sum_{i=1}^{p} \phi_i \begin{pmatrix} \Delta P_{cash,t-i} \\ \Delta P_{Fut,t-i} \end{pmatrix} \tag{1}$$

where $\Delta P_{cash,t}$ is the change in the price of the cash market, $\Delta P_{fut,t}$ is the change in the price in the (conversion-factor-adjusted) futures market. The analysis of the prices in the two markets also allows us to investigate the patterns in the basis B_t over time, i.e., the difference between the price of the underlying deliverable cash bonds and the futures price (corrected by the conversion factor). We expect β, the co-integration vector, to be $(1, -1)$, hence supporting the arbitrage condition, and we expect α to indicate that most price discovery happens on the futures market.

IV.B Liquidity Discovery

We aim to investigate the dynamic inter-relation of the liquidity in the two markets. In order to distinguish between long- and short-term adjustments, we analyze this relationship at a daily level (in levels) and at the intra-day level (in differences). As discussed above, the liquidity in the two markets is substantially different, with the futures market being much more liquid, while the liquidity in the cash bond market is distributed over several cash bonds with different maturities and coupons. However, since the cash bond is the security underlying the futures market, we expect the liquidity in the cash bond market to have an influence on the liquidity of the futures contract, and vice versa.

We need to distinguish between the change in the liquidity that comes from a change in the information set available to investors, which will likely move from the futures market to the cash market (as argued above), and shocks to liquidity that originate purely from asset liquidity changes, such as lending difficulties and those following the ECB interventions, which we expect to move from the cash to the futures market. However, we need to bring into the picture the behavior of arbitrageurs that is largely affected by the level of the basis, the level of the liquidity and the volatility of the liquidity in both markets; these characteristics of liquidity have an important influence on arbitrageurs' ability to implement arbitrage actions. To address this issue, we estimate a VAR at a daily frequency, using the level of the basis and liquidity measures in the two markets as endogenous variables, and consider the impulse response functions in order to understand the overall effect of one variable on the others.

Formally, the model we investigate is:

$$\begin{aligned} QS_{cash,t} &= \alpha + \sum_{i=1}^{p} \beta_i QS_{cash,t-i} + \sum_{i=1}^{p} \gamma_i QS_{future,t-i} + \sum_{i=1}^{p} \delta_i B_{t-i} \\ QS_{fut,t} &= \alpha + \sum_{i=1}^{p} \beta_i QS_{cash,t-i} + \sum_{i=1}^{p} \gamma_i QS_{future,t-i} + \sum_{i=1}^{p} \delta_i B_{t-i} \end{aligned} \tag{2}$$

where $QS_{cash,t}$ and $QS_{fut,t}$ represent, respectively, the *Quoted Spreads* in the cash and futures markets, and B_t represents the basis. The level of the basis implies potential arbitrage opportunities between the two markets, and therefore potential incentives for arbitrageurs to exploit these opportunities. In principle, if the basis were zero, this analysis would capture just the stickiness of the liquidity adjustment.

However, the analysis at the daily frequency focuses on both the long-run (interday) and short-run (intraday) adjustments of the basis and liquidity in the two markets. The adjustment mechanisms may be different depending on the frequency of trading; intraday adjustments of the basis and the spillover effects of liquidity between the two markets may be different from those between days. Formally, the model we investigate is:

$$\begin{aligned} \Delta QS_{cash,t} &= \alpha + \sum_{i=1}^{p} \beta_i \Delta QS_{cash,t-i} + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i} \\ \Delta QS_{fut,t} &= \alpha + \sum_{i=1}^{p} \beta_i \Delta QS_{cash,t-i} + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i} \end{aligned} \tag{3}$$

where $\Delta QS_{cash,t}$ and $\Delta QS_{fut,t}$ represent, respectively, the changes in the *Quoted Spreads* in the cash and futures markets, and ΔB_t represents the change in the basis. It is clear that changes in the basis imply changes in the arbitrage relationship between the two markets. Once this effect is controlled for, the remaining component can be attributed to shocks to liquidity due to trading, funding liquidity, or other causes that do not directly affect the relative pricing of the futures contract and the underlying cash bond.

However, the *Quoted Spread* is only a first approximation of the liquidity of the market, since traders might place a symmetric bid-ask spread around the value of the security (midquote) and adjust the bid and ask quotes equally, when the basis changes. In contrast, they might demonstrate their willingness to buy or sell by changing the quoted quantity at the best bid and ask, but also in the other bid- and offer-price levels, just behind the current level of the market. Since market makers in the cash market are judged by MTS as well as the *Tesoro* according to their presence at the best bid and offer prices over time, they have a clear incentive to keep the price aligned to the best quotes. Nonetheless, a lower willingness to trade would show up in the overall book. Hence, we need to introduce a liquidity metric that takes this effect into consideration.

IV.C The Asymmetric Effect of Liquidity on Price

The measure that allows us to actually discriminate between the willingness of market makers to buy and their willingness to sell needs to take into account both the depth and level of the book. Hence, we calculate the λ measure, in the spirit of Kyle (1985): How much would a trader move the price, if he or she were to buy €15 million worth of the bond? How much, if he or she were to sell the same amount? We call these quantities λ^A and λ^B, respectively, and we are thus able to investigate the liquidity discovery effect.

Therefore, we repeat the analysis in the previous section, using λ to capture the liquidity of the cash market, expecting different results for the liquidity at the bid price and the liquidity at the ask price. We aim to characterize the effect that a shock in the liquidity of one market has on the liquidity of the other market, when an arbitrage opportunity between the two markets is available, and control for it.

$$\begin{aligned}
\Delta\lambda^A_t =& \alpha + \sum_{i=1}^{p} \beta^A_i \Delta\lambda^A_{t-i} + \sum_{i=1}^{p} \beta^B_i \Delta\lambda^B_{t-i} + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i} \qquad (4)\\
\Delta\lambda^B_t =& \alpha + \sum_{i=1}^{p} \beta^A_i \Delta\lambda^A_{t-i} + \sum_{i=1}^{p} \beta^B_i \Delta\lambda^B_{t-i} + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i}\\
\Delta QS_{fut,t} =& \alpha + \sum_{i=1}^{p} \beta^A_i \Delta\lambda^A_{t-i} + \sum_{i=1}^{p} \beta^B_i \Delta\lambda^B_{t-i} + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i}
\end{aligned}$$

IV.D Limits to Arbitrage

In order to close the circle of the relationship between liquidity and arbitrage opportunity, we investigate the effect that impaired liquidity has on the basis between the cash and futures contracts.

At the daily frequency, we consider the following relationship:

$$B_t = \alpha + \sum_{i=1}^{p} \beta_i QS_{cash,t-i} + \sum_{i=1}^{p} \gamma_i QS_{future,t-i} + \sum_{i=1}^{p} \delta_i B_{t-i} \tag{5}$$

to gauge how the level of illiquidity in the markets prevents arbitrageurs from taking advantage of the discrepancies between the prices. However, this analysis captures the long-term effects on the level of the basis.

We aim also to investigate intraday short-term effects, and in this case we study how the changes in the basis are due to changes in the liquidity conditions of the markets. We therefore investigate the following relationship:

$$\Delta B_t = \alpha + \sum_{i=1}^{p} \beta_i \Delta QS_{cash,t-i} + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i} \tag{6}$$

Finally, to study how the willingness of the market makers to trade in the cash market affects the changes in the basis, we also estimate the following equation:

$$\Delta B_t = \alpha + \sum_{i=1}^{p} \beta_i^A \Delta \lambda_{t-i}^A + \sum_{i=1}^{p} \beta_i^B \Delta \lambda_{t-i}^B + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i} \tag{7}$$

to gauge how the illiquidity in the markets prevents the arbitrageurs from taking advantage of the discrepancies between the prices.

IV.E ECB Intervention

Pelizzon, Subrahmanyam, Tomio, and Uno, 2016 show that a major ECB intervention (LTRO) had a sharp effect on the relationship between the liquidity in the market for sovereign bonds and the credit risk of the security underlying the futures. In investigating how the liquidity in the cash and futures markets affects the basis, we expect that the ECB intervention, in modifying the relationship between credit risk and liquidity, also had an effect on the arbitrage relationship.

If there is credit risk in the underlying security, borrowing that security will be more difficult and the borrowing will take place at a more uncertain level (leading to a high variance of the EUREPO rate, the general repo rate for European bonds). The ECB intervention, by reducing the effect of the credit risk on the market liquidity, fostered the convergence of the basis to zero, and the speed of adjustment should reflect this. In order to test this proposition, we split the sample following Pelizzon et al. (2016) and re-estimate our model for the two samples separately.

IV.F Computational Issues

A large number of observations would support the use of asymptotic variance-covariance matrices in the VAR specification. However, due to some "outliers" that we do not want to discard, the usage of heteroskedasticity-robust standard errors is our preferred solution. Moreover, since the VAR approach is merely a linearization of a possibly more complicated and non-linear dependency between the endogenous variables, we have reasons to believe that a bootstrapping approach to the estimation of the covariances is advisable. We thus perform our analysis by both estimating the (asymptotic) heteroskedasticity-robust variance-covariance matrix and bootstrapping it. We report the results for the asymptotic version; however, the results are robust to the bootsrapping procedure.

V Results

V.A Basis

The price of the futures contract and that of the underlying bond are bound to converge at delivery, by definition. However, many bonds can be delivered to the investor who is long a futures contract, by the trader who has a short position on the same futures contract, and the deliverable bonds usually differ with respect to time to maturity, coupon, and, hence, duration. For the 10-year BTP futures contract with delivery month June 2011, for example, six different bonds could be delivered, with coupons ranging from 3.75% to 4.75%, time to maturity ranging from 8.7 to 10.4 years, and duration ranging from 7.2 to 8.5 years.[10]

The futures contract is based on a hypothetical bond with a 6% coupon; hence, its price needs to be adjusted to match that of the delivered security. This is done via the use of a conversion factor. The conversion factor is the price that a bond with the same coupon rate delivering one dollar at maturity would have if it was priced at delivery with a yield of 6%. The investor who is long in the futures contract will, at delivery, pay $F_t \cdot CF_I$, where F_t is the futures price agreed when the contract was created at time t and CF_i is a bond-i-specific conversion factor, while the investor who is short in the futures contract will deliver bond i.

Due to the conversion factor conventions, among other determinants, when several bonds are deliverable for the same futures contract, a specific bond will generally be identified as the cheapest-to-deliver (CTD) because it is the bond that the investor who is short can buy on the market and deliver while suffering the smallest loss. Formally, the CTD bond at time t for a futures contract signed at time τ will be the bond i such that $i = \arg\min_i FP(i,t) - F_\tau \cdot CF_i$, where $FP(i,t)$

[10]Recall that the 10-year BTP futures contract allows the delivery of any standard fixed coupon-bearing bond issued by the Italian government with time to maturity on delivery of between 8.5 and 11 years.

is the forward price for bond i. The quantity

$$FP(i,t) - F_t \cdot CF_i \tag{8}$$

for the CTD bond i is the futures-bond basis at time t. Appendix A elaborates on how several details, among others regarding the institutional setting, need to be taken into account when calculating the basis.

The basis for each futures contract and each deliverable bond are shown in Figure 1. The detailed analysis of the CTD bond shows that, on the vast majority of trading days, the CTD (the bond with the smallest basis) is also the on-the-run 10-year bond. Figure 2 shows the time-series of the basis computed relative to the price of adjusted price of the CTD bond. The data presented here are sampled at a five-minute frequency, which contributes to the volatility of the basis; however, the long-term movements of the basis can be clearly discerned. The basis was large and positive during the second half of 2011, reaching a maximum of 130 bp, while in 2012 it slowly approached the arbitrage-free value of 0, with the basis for the contract deliverable in December 2012 finally oscillating between 10bp and -10bp. Varying bid-ask spreads in both markets affect the size of basis shown in Figure 2 since we compute them using mid-quotes of the cash bonds and the futures contract.

Insert Figure 1 here.

Insert Figure 2 here.

As per the formula above, the basis is the difference between the futures price and the bond price, up to a linear scaling, as detailed in Appendix A. The two variables are plotted in Figure 3 for the CTD. As Figure 2 suggested, a sizable gap can be spotted between the variables in the second half of 2011, while in 2012 the gap between the two series is practically indiscernible. As a matter of fact, their correlation is 99.8%.

Insert Figure 3 here.

To provide a better indication of the actual profits an arbitrageur could have earned after taking into account the bid-ask spread, we introduce the concept of the "executable basis". The "executable basis" is computed by assuming the purchase of the futures (cash) contract at the ask-price and the sale of the CTD cash bond (futures) at the bid-price in the presence of a positive (negative) basis. In this calculation, we ignore execution risk associated with competition among arbitragers. Figure 4 Panel A shows the time-series evolution of the executable basis when buying futures and selling cash bonds, in comparison with the basis using the mid-quotes. The difference between the two basis calculation was larger during the second half of 2011, however, it remains around € 0.1 which is equivalent to a half of the average bid-ask spread of the two instruments.

Figure 4 Panel B shows that the profitability (executable basis) of the two strategies, buy futures and sell cash (shown in blue) and vice versa (shown in red), in relation to each other. The blue line stayed above zero during early part of second half of 2011, indicating that arbitrage activity did not eliminate price discrepancy between the futures and cash market.

Insert Figure 4 here.

The time-series evolution of the bid-ask spreads for the CTD bond and the futures contract are shown in Figure 5. In order to reduce the noise, the five-minute interval liquidity measures used in the analysis were averaged to obtain the daily measures. Although the scales are different, since the bid-ask spread for the futures is generally more than ten times smaller than the bid-ask spread for the bond, it is clear that the two variables move with a strikingly similar pattern. The spikes in the first half of the graph are common to both measures, while in 2012 the illiquidity of both markets plummeted to the levels of early-2011. The tight relationship between the two series can also be inferred from the simple correlation between them, which is 73%.

Insert Figure 5 here.

Table II shows the descriptive statistics of both the futures contract and the corresponding CTD bond specifically used in our subsequent analysis. For our analysis, we employ both daily and intraday data so as to discern the possible discrepancies between the long- and short-term effects, where daily data are obtained by averaging the corresponding observations sampled at a five-minute frequency. Descriptive statistics for the daily level are presented in the panel on the right-hand side of the table and the five-minute frequency on the left-hand side. The table shows that the bid-ask spread for the CTD bonds is, on average, €0.25 per €100 of face value; however, the median is 0.19 for the five-minute frequency, and 0.20 for the daily data, indicating a significant asymmetry in the distribution. Moreover, the standard deviation is also very large, at 0.24 for the five-minute and 0.20 for the daily data, indicating a large variability in the bid-ask spread for the sample period considered, as already highlighted in the figures presented above.

The related statistics are quite different for the futures market. In this case, the bid-ask spread is, on average, very low, at €0.03 per €100 of face value, and the median is very similar to the mean indicating a relatively symmetric distribution. A comparison between the bid-ask spread of the CTD bond and that of the futures market shows a ratio with an order of magnitude of 1 to 8. The standard deviation is also very low, at 0.020 at the five-minute frequency, and 0.010 at the daily level, the latter being roughly one half of the five-minute standard deviation. This means that, compared with the standard deviation (and therefore the potential execution risk) in the bond market, the five-minute standard deviation is 10 times lower, and at the daily level is 20 times lower.

For the cash bond market, we have information that allows us to calculate the lambda measure, which represents the depth of the book, and therefore the depth of the market. This depth measure ranges, on average, from 0.0158 for the ask, to 0.0166 for the bid, with a difference, on average, of -0.001, which means that trading €15 million would move the bid- or ask-price by €0.0158 or €0.0166 per bond, on average, toward the side of the market hit by the order. After averaging to obtain a daily time series, this measure is, on average, slightly higher. This measure, however, is highly volatile in the sample period considered, as indicated by the standard deviation at the five-minute frequency equal on average to 0.045, which is more than three times larger than the means, and by the time evolution of the series shown in Figure 6. It is interesting to observe that the standard deviation of the difference between λ^A and λ^B is 0.04574, which is of the same magnitude as the two lambda measures, indicating the presence of significant imbalances between the two measures, and therefore, between the two sides of the market (that is, there is a significant and negative correlation among the two measures). Daily data, based on the average of the five-minute changes, smooth out a lot of this effect, resulting in a smaller standard deviation than that for the five-minute interval. This time-series is shown in Figure 7.The difference between the two variables shows an even lower standard deviation, indicating that asymmetries in the book cannot be captured well by looking at the daily average of this measure.

Insert Table II here.

Insert Figure 6 here.

Insert Figure 7 here.

V.B Price Discovery

In order to estimate whether the data support the theoretical prediction of a one-to-one arbitrage between the price of the on-the-run bond and the futures price, up to a linear transformation, we estimate the co-integrating relationship described in Equation 1 using both the average of the daily price and the five-minute pricing data. First, however, we verify that the two series statistically have unit roots, hence justifying the use of the co-integration framework.

Our unit root analysis shows that both series test statistically significant for the presence of unit roots, regardless of the alternative hypothesis – the most appropriate alternative hypothesis is that of a stationary variable with a non-zero mean and no trend, hence ruling out trend-related arbitrage possibilities. The Bayesian criterion selects a lag specification such that there is no short-term adjustment in the price levels when we analyze the daily data.

Table III shows the results of the co-integration analysis. In Panel A, the results of the trace test under the restriction of "no time trend". are shown both for the daily and the intra-day level. The test cannot reject the alternative of rank 0 at a 5% significance level, while it cannot reject the null of rank 1, at the same significance level, for either the five-minute or daily frequency data. The variables, thus, co-integrate with a β-vector which is, for the 5-minutes data, $(1 \cdot \text{BondPrice}_t - 1.00268 \cdot \text{FuturesPrice}_t)$, as shown in Panel B. The coefficient for the futures price is very close to 1 and, in fact, the test for $\beta = (1, -1)$ cannot reject the null that the difference between the prices is in the co-integration space (P-value = 0.80), namely that the simple difference between the futures price and the bond price is a stationary variable. Again, this result holds for both the 5-minute and the daily frequency data.

Insert Table III here.

The adjustment coefficients shown in Panel B indicate that, while the futures price does not adjust to equilibrium, since the corresponding α and β elements have the same sign, all the adjustment is made by the bond price and the results are consistent between the daily and intra-day analysis. For the five-minute frequency, the lag-length of the VAR underlying the co-integration analysis is 6, which was chosen as a parsimonious model according to the Bayesian criterion. For the price of the futures equation, 4 out of 10 short-term adjustment coefficients are significant, as shown in Panel C, while 10 out of 10 are significant for the bond price regression, indicating that the bond price is also adjusting in the short run to movements in the futures price, while correcting the overshooting that takes place in the cash price. For the daily frequency, the lag-length of the VAR is zero as expected. Therefore, the entirety of the long-term price adjustment takes place on the same day in the cash market, hence the lack of need for short-term adjustment factors. Price discovery among these two markets is just an intra-day effect, contrary to the findings of several prior studies in other markets.

V.C Liquidity Discovery

To address issues related to liquidity discovery and limits to arbitrage we need to analyze the interaction between these two effects using a VAR model. More specifically, we aim to investigate whether shocks to the market liquidity spill over into the other market, whether the liquidity of one market drives that of the other, and whether the low market liquidity in the cash or futures market is an impediment for arbitrageurs who focus on exploiting discrepancies between the prices in the two markets. On the other hand, we would like to investigate whether the behavior of arbitrageurs who aim to exploit the departure of the basis from zero generates a potential liquidity spillover effect. More formally, the VAR model we estimate is a combination of Equations 2 and 5.

We estimate the VAR using both daily data and five-minute intraday data. The analysis with daily data is aimed at capturing long-term effects and is performed in levels. We choose the lag-length using the Bayesian criterion, selecting a lag-length of 4, which is very different from the lag-length used for the regression in Equation 1 that indicated the presence of no lagged adjustment in the price at the daily level. The four lags we find indicate the presence of substantial stickiness in the liquidity measures. We then perform Wald tests to verify, for each equation, whether the four lags of each variable are all statistically different from zero. Table IV shows the results of the tests, where each value in the table is the Wald-test statistic for testing whether the four lags of the row-variable are all contemporaneously statistically zero in the column-variable equation. The test values are calculated using heteroskedasticity-robust variance-covariance matrices.

Table IV shows surprising results. At the daily level the liquidity of the bond market, measured by the average of the bid-ask spread of the day, lead the liquidity in the futures market in a strong and significant fashion. The bid-ask spread also leads the price impact on the opposite side of the market. The liquidity in the futures market strongly affects only itself and has no price impact.

Insert Table IV here.

How can the above results be explained? First, it should be noted that the architectures of the cash and futures markets in Italian sovereign bonds vary significantly from each other. The cash market is dominated by market makers (as designated by the MTS), who are roughly the same group as the primary dealers who bid at the auctions run by the *Tesoro*, the Italian Treasury. These entities have obligations to make markets and also bid at the Treasury auctions. In contrast, the futures market has only one designated market maker, and any investor can place a limit order, substituting for the role of the market makers. Because of this structural difference, liquidity measures in the cash market reflect directly the behavior of professional market makers acting similarly, whereas in the futures market, liquidity measures become stale quickly due to the mixture of actions taken by a variety of market participants. Second, the cash bond market is much larger in terms of volume of trading than the futures market, although it is dispersed across several individual bonds. However, the bid-ask spread in all bonds, including the on-the-run benchmark bonds, is much higher and more volatile than their futures' counterpart: the mean bid-ask spread of the on-the-run bond is about ten times as large as that of the futures contract and about twenty times as volatile (at the daily frequency). This implies that many arbitrage opportunities are not executable, due to poor liquidity in the cash market, which we examine implicitly in our computation of the executable basis in Figure 4 Panel A and B. Also, given the volatility of the bid-ask spread, an arbitrageur would typically consider the liquidity of the cash leg first, due to its relatively paucity and risk of execution.

The impulse response functions can be used to assess the magnitude and sign of a shock to one variable to the whole system. We orthogonalize the shocks so that we can separate the direct effect of a variable from the effect of a shock to a variable which would be correlated to the shocks to the rest of the system.

Figures 8 shows that an orthogonal 0.6 standard deviation shock to the liquidity of the bond market has a long lasting same-sign 0.2 standard deviation effect on the liquidity of the futures market. The net basis is significantly positively shocked for four days and a 0.6 standard deviation shock to the bond liquidity has a 0.1 standard deviation effect on the mispricing between the two sovereign markets. The net basis, on the other hand, is shown not to be affected by a change in the liquidity of the futures market, which, however, marginally affects the bond market. A shock to the net basis does not significantly affect either markets' liquidity, having only a long lasting effect on itself.

Insert Figure 8 here.

When we perform the short-term analysis based on intraday data, we look to adjustments with respect to the average results of the day already analyzed. More formally, the VAR model we estimate is a combination of Equations 3 and 6. So, in this case, we concentrate on the changes in the bid-ask spreads for the CTD bond and the futures contract, and the changes in the basis. We choose the lag-length using the Bayesian criterion, selecting one of 16, which is higher than the lag-length used for the regression in Equation 1 due to the high degree of stickiness of the liquidity measures. We then perform Wald tests to verify, for each equation, whether the 16 lags of each variable are all statistically different from zero. Table IV shows the results of the tests, where each value in the table is the Wald-test statistic, testing whether the 16 lags of the row-variable are all contemporaneously statistically zero in the column-variable equation. The test values are calculated using heteroskedasticity-robust variance-covariance matrices.

Table IV again shows surprising results. The liquidities of the two markets seem not to affect each other, once their own lags are taken into account. Each variable seems only to be explained by itself. This result is surprising, and not in line with the findings of Roll et al. (2007), although their analysis is performed in levels, and not in changes, which may be driving the differences in the results. A possible explanation of these results could be that there is a basic difference between the long-term (i.e., daily) and short-term (intraday) results. While the short-term liquidity in the cash bond market can be affected by the quotes posted by a single market maker, the long-term liquidity is determined by the consensus of all market makers.

However, as maintained in Section IV.B, these results are obtained by considering a liquidity measure that cannot distinguish between a change in the willingness to buy and a change in the willingness to sell. The λ measure, specifically its two components λ^A and λ^B, on the contrary, can measure which side of the market is "thickening" or "thinning" hence allowing us to discriminate between the changes in the market makers' willingness to take the two opposite sides.

The Asymmetric Effect of Liquidity on Price

We re-estimate the VAR, substituting the bid-ask spread measure for the bond market with the two components of λ, λ^A and λ^B, as in Equation 4. The estimates of the Wald test for this specification are presented in Table V. Contrary to the findings for Equation 3, the liquidity of the bond market measured by the price impact at the bid can be show to lead the liquidity in the futures market in a strong and significant fashion. λ^B also leads the price impact on the opposite side of the market. The liquidity in the futures market strongly affects only itself, while it is weakly significant in terms of its effect on the price impact on the ask side of the bond market.

Insert Table V here.

These results can be interpreted as follow. When the basis in Equation 8 is positive, as is the case for most of our sample, the bond price is higher than the futures price. Market makers could lock in a risk-free profit, if they managed to sell the bond and buy the futures simultaneously, while avoiding having their bids hit by another dealer. Therefore, after controlling for the change in the futures market liquidity, and the basis, when the basis is positive, a change in the willingness to sell, i.e. more aggressive ask-pricing, implies the market makers' propensity to close the basis, which translates into aggressive buying pressure in the futures market, where the liquidity will instead dry up.

A similar, but diametrically opposite argument, however, could be made for movements in the price impact on the bid side, even though these movements are shown to have much lower explanatory power according to the Wald tests. If our reasoning was correct, it would be the "excess selling pressure" that moved the futures market liquidity, meaning the extra willingness of the market makers to buy, rather than to sell. We calculate the difference between λ^A and λ^B and repeat the analysis.

The VAR system in Equation 7 confirms our intuition. The difference between the λ^A and λ^B, which we call the excess selling pressure, is statistically significant in leading the liquidity in the futures market, as shown in Table VI. We interpret this result as the effect of the market makers' attempt to try and profit from the mispricing between the futures and the bond market. As the price discovery happens in the futures market, new information is included in the prices of that market. The cash market on the other hand participates in closing the basis so that the market makers price their ask-side more aggressively and allow the price of the bond to converge to that of the futures. [11].

Insert Table VI here.

V.D Limits to Arbitrage

One of the striking results of our paper is that the basis generated by two relatively very liquid markets (the cash and the futures bond markets) remains persistently positive (or negative) for several days. Arbitrage activities should have eliminated this deviation of the basis from zero. Therefore, it is important to investigate whether, on one side of the market, the low liquidity in the cash or the futures market is an impediment for arbitrageurs, and how changes in these conditions affect their behavior, in turn the basis, and therefore the market liquidity of these two markets.

[11]The wiilingness to trade and its impact on the bid-ask spread of the futures contract and on the basis is specifically an intraday effect. At the daily level, this imbalance or asymmetry of the book almost disappears, as shown in Table II. For this reason, we do not include a similar analysis based on daily data in this paper. However, for completeness, we did perform this analysis and, as expected, the changes in the lambda measures at the daily level do not affect the changes in the bid-ask spread of the futures contract or the changes in the basis

When we look at the daily analysis that is based on levels, Table IV shows that the basis is persistent on one side, so it depends on its level the day before but is also largely driven by the liquidity in the cash bond market. This result is confirmed when we look at the impulse response function analysis.

We interpret this finding as supporting the limits-to-arbitrage argument, which predicates that liquidity, whether in its funding or market counterpart, keeps prices from converging to arbitrage-free levels, at which they should be, in theory. The key aspect of our findings is that, in fact, liquidity in the cash market is the largest constraint on arbitrage activity. As soon as the bid-ask spread in the cash market moves to a reasonably low level, it induces arbitrageurs to step in with arbitrage action. Indeed, this is the main explanation for it being the liquidity in the cash market that leads both the basis and the liquidity in the futures market. This leads to the conundrum that, even if the price discovery happens in the most liquid market, it is the most illiquid one that drives the basis and therefore the resultant liquidity spillover effects.

These results are confirmed when we move to the intraday level. In this case, we investigate how changes in the willingness of the market makers to trade affect the changes in the basis (independently of the level of the bid-ask spread or the basis itself). When considering the movement of the basis, Table IV would suggest that changes in the bid-ask spread do not reflect the movements in the basis, but that only the levels matter. However, we find that, in Tables V and VI, the two components of liquidity do lead the movements in the basis. This indicates that, in the short run, changes in the basis are primarily driven by market participants' willingness to trade in the cash bond market. This means that intraday changes in the basis are largely driven by the actions of arbitrageurs. In the cash market, arbitrage activity helps to close the basis so that the market makers price their ask-side more aggressively and allow the price of the bond to converge to that of the futures contract, or to a different basis more in line with the new level of the bid-ask spread in the cash market.

V.E ECB Intervention

By virtue of its status as the central bank of the Euro-zone, the ECB has a major influence on its sovereign bond markets. The ECB's monetary intervention takes many forms ranging from formal guidance by its board members, in particular its President, to injection of liquidity into the major banks in the Euro-zone which themselves hold these bonds, and to direct purchases of sovereign bonds in the cash markets. These actions are likely to have an impact on the liquidity in the cash bond markets as well as on the basis between the Euro-zone cash bonds and the respective bond futures contracts.[12] Of course, the direction and magnitude of this impact would depend on the nature and size of the interventions over time. During the Euro-zone crisis, the intervention by the

[12]To this day, the interventions were never conducted directly through the purchase of the futures contracts, and hence their liquidity has never been directly affected.

ECB took many forms: (i)the Securities Market Programme(SMP), (ii) Long Term Refinancing Operations (LTRO), (iii) Policy Guidance and (iv) Outright Monetary Transactions (OMT). We discuss these programs below in the context of their impact on liquidity discovery.

The ECB defines the SMP as follows: "Interventions by the Eurosystem in public and private debt securities markets in the euro area to ensure depth and liquidity in those market segments that are dysfunctional. The objective is to restore an appropriate monetary policy transmission mechanism, and thus the effective conduct of monetary policy oriented towards price stability in the medium term. The impact of these interventions is sterilized through specific operations to re-absorb the liquidity injected and thereby ensure that the monetary policy stance is not affected."[13]

The SMP was initiated in May 2010 in the aftermath of the Greek debt crisis, which spilled over into the sovereign debt market of several countries in the Euro-zone. The distinctive feature of the program is the direct purchase of sovereign debt securities in the open market by the ECB with the intent of retaining them on its balance sheet until maturity ("hold-to-maturity strategy"). However, several features of the program were not made explicit at that time or since then. In particular, the amounts proposed to be spent, the time frame over which the purchases would occur, or the specific securities that would be purchased, were not announced. However, data on the outstanding aggregate value of the holding portfolio were published, albeit at a weekly frequency, without any reference to the specific date(s) during the week when the securities had been bought. Furthermore, the ECB did not provide a breakdown describing the composition of these assets by national origin of issuance, maturity, coupon or other characteristics.[14] We use the data on weekly, public available purchases of debt securities under the SMP in our analysis. Since the SMP targeted sovereign debt securities in the cash markets (without corresponding action in the futures markets), we expect an immediate widening of the basis around purchases, due to the sheer size of these interventions.

The second intervention measure, LTRO, is formally defined by the ECB as follows: "A regular open market operation executed by the Eurosystem in the form of a reverse transaction. Longer-term refinancing operations are carried out through monthly standard tenders and normally have a maturity of three months but on December 8th the ECB announced the 3year LTROs that consist of 3-year collateralized loan and belong to the set of non-standard measures launched by the ECB. Concretely, the 3-year LTROs provided EUR 489billion on 21 December 2011 and EUR 523 billion on 29 February 2012. [15]

Unlike the SMP, information regarding LTRO is very sparse and does not allow us to measure the quantitative impact of this extraordinary ECB measure, and hence, assess its quantitative

[13]See http://www.ecb.europa.eu/home/glossary/html/act4s.en.html .

[14]The ECB disclosed details of the securities holdings acquired under the program revealing a country-by-country breakdown, on one date, February 21, 2013. As of that date, Italian debt accounted for roughly half the total (€103 billion out of a total of €218 billion). Spain ranked second (€44 billion), followed by Greece (€34 billion), Portugal (€23 billion) and Ireland (€14 billion. See Corradin and Rodriguez-Moreno (2014.).

[15]See http://www.ecb.europa.eu/home/glossary/html/act4s.en.html.

impact on market liquidity in the sovereign bond market. We expect that the availability of massive amounts of funding from the ECB, at unusually low interest rates, should have shifted the incentives of banks to hold sovereign bonds, which could be pledged as collateral for the funding. However, since the banks' use of this funding facility was likely to have been gradual (although we have only anecdotal information on this), it did not have a direct and immediate influence on the basis between the cash bonds and the respective futures contract. Rather, in contrast to the positive basis resulting from the SMP, we expect the size of the basis to significantly decline after the LTRO measure toward zero.

The third instrument is the policy guidance offered by the ECB through various policy pronouncements by its board members, most prominently the comment by the President, Mario Draghi, to do "whatever it takes "to address the Euro-zone crisis, in July 2012.[16] This served to restore confidence in the markets and was also likely to reduce the basis between the cash and futures markets to zero.

The last type of intervention employed by the ECB is the OMT program, under which it could make purchases ("outright transactions") in the secondary, sovereign bond markets of the Euro-zone countries, subject to strict conditions. However, although the operation was announced on August 2, 2012, the technical framework of these operations was formulated only on September 6, 2012, but has not been formally adopted until today. Indeed, the legal basis of these purchases has been challenged and is currently being adjudicated by the Federal Constitutional Court of Germany, in Karlsruhe, and perhaps, ultimately, by the European Court of Justice, in Luxembourg.

Figure 9 shows the time line of these interventions during the period June 2011 to December 2012. The differing impacts of these interventions can be analyzed by examining the time-line of these interventions (and their intensity), in relation to the dynamics of the basis over time.The figure shows the amounts bought by the ECB, at a weekly level, under the SMP intervention framework, and the basis between the cash bond that is CTD and the futures contract on the BTP bonds (indicated by the orange line). Although the ECB bought the sovereign bonds of several of the stressed Euro-zone countries, these data are, unfortunately, not available in the public domain. In the absence of detailed weekly data by country, we expect that the total volume of the amount bought by ECB may be a reasonable proxy for the pattern of purchases of Italian sovereign bonds (see also footnote 14 above).

Insert Figure 9 here.

At a broad level, our analysis of Figure 9 suggests that during the period between the first week of August 2011 and the first week of January 2012, the buying pressure from the SMP caused the cash bond prices in the BTP market to increase, without a corresponding adjustment in the futures price, since the ECB only intervened in the cash markets. This caused the basis to stay positive

[16] In his speech on July 26, 2012, at the Global Investment Conference in London, Mario Draghi stated: "The ECB is ready to do whatever it takes to preserve the Euro. And believe me, it will be enough."

until the last week of October 2011, during which period arbitrageurs were reluctant to try close the basis gap, due to highly volatile conditions in the Italian sovereign bond market, as well as restrictions on their funding liquidity, and the poor liquidity in the repo market, which made it difficult to borrow the cash bonds that should have been shorted to take advantage of the basis.[17] A striking confirmation of our intuition is that the basis increased by 60 basis points during the last week of July 2011, when the ECB bought €22 billion of sovereign bonds. The resignation of the government headed by Berlusconi, in the second week of November, caused panic selling by several market agents, causing the basis to turn negative, despite the SMP.

The LTRO was announced in the second week of December 2011, but took effect in the last week of December 2012. This massive infusion of liquidity alleviated the panic in the cash bond market, while easing the constraints on funding liquidity. This caused the basis to converge to zero, indicating the elimination of arbitrage opportunities. Subsequent to these actions, the basis nearly closed and by the time that the ECB President made the "whatever it takes"comment in July 2012, the markets were quite liquid, allowing a smooth shock transmission between the cash and futures market. Indeed, the widely anticipated OMT policy instrument has not been used, at least as of the time of this writing.

Unfortunately, the weekly data about SMP does not allow us to perform a proper Granger causality analysis, since the basis spikes largely in the same week as when the ECB made its largest purchases; this contemporaneity of the weekly data does not allow us to disentangle the two factors to verify if there is any causality effect between the two variables. Regarding LTRO, the information available is even less detailed, since we know only the *total* amount issued in the two tranches, but have no information on the bank-specific amounts involved and, more importantly, the time series and ways of the use of these funds by the banks. However, what the figure clearly indicates is that after the LTRO intervention, the basis slowly converged to zero.

In the context of this lack of detailed data, we nevertheless investigate whether we can detect a structural break in the relationship between cash and futures market liquidity and the basis, but are unable to find any statistically significant structural break in the data at the daily level.[18] This confirms that the basis is largely driven by the frictions (i.e., due to the low liquidity in the cash market) and as soon as the bid-ask spread in the cash market significantly reduced (see the red line in Figure 9), the basis reduced as well, and converged to zero. We find that the LTRO intervention of December 2011 had a profound effect on the liquidity of the bond market (in line with the finding of Pelizzon et al. (2014)). Following this, we examine whether we can detect any structural break in the relationship, at the intraday level, among the three variables. In other words, we split the sample in two subsamples to check if the lead-leg relationship that we find in the full sample is confirmed. In particular, we split the sample before December 1st 2011, and after January 1st

[17]This has been confirmed in our conversations with prominent market participants.

[18]Both the recursive and OLS residual cumulative sum tests (the Rec-CUSUM and OLS-CUSUM test respectively) were not significant at conventional significance levels.

2012, and repeat the analysis in Equation 7.

We find that our results at the intraday level are driven by the first part of the sample, where the differences in the market depths (the "lambdas") drives both the basis and the liquidity in the futures market. On the other hand, in the subsample starting January 1st 2012, the dynamics of the variables are almost solely dictated by their own past movements. The enhanced liquidity that the market makers were able to funnel into the cash market, together with a very small basis in the latter period, keeps us from finding any lead-lag relationship between the variables at a 5 minute frequency.

Overall, we can conclude that the LTRO interventions by the ECB not only improved the liquidity in the Italian sovereign bond market, but also facilitated the process of liquidity discovery between the cash and futures markets in Italian sovereign bonds. Further, these measures alleviated the limits to arbitrage in these markets and gradually caused the basis between the cash and futures market to decline towards zero.

VI Conclusions

The Euro-zone sovereign debt markets are an ideal laboratory for investigating issues related to liquidity discovery and limits to arbitrage for several reasons: (i) the availability of high-frequency data for both the cash and futures markets allows us to determine how the adjustment occurs in the age of algorithmic trading, where market discrepancies are acted on in a matter of minutes, if not seconds, (ii) the cash asset and the futures contract based on it are traded *directly* (rather than being baskets of assets that are traded individually, as in the case of stock indices) in relatively liquid markets, which permits us to investigate the mechanism of liquidity discovery in depth, and (iii) the market was buffeted by several information shocks during the crisis, due to significant market uncertainty as well as the possibility of policy intervention, thus providing sufficient variation in liquidity discovery and transmission over time, especially under conditions of extreme market stress. In this setting of the Italian sovereign bond market, our framework permits us to investigate several issues regarding price and liquidity discovery, and their interactions with limits to arbitrage, by observing the market microstructure of the futures and underlying cash bond markets. Surprisingly, we find that, although the futures market leads the cash market in price discovery, as documented in the prior literature, the cash market leads the futures market in liquidity discovery, i.e., the willingness of the market makers to trade, as measured by the depth of the market.

Moreover, the liquidity in the cash market also has a significant impact on the changes in the basis between the prices of the cash bond that is cheapest to deliver, and the futures contract, thus helping to explain the drivers of the limits to arbitrage in these highly liquid markets. Our empirical results indicate that the cash bond market is characterized by greater illiquidity and liquidity risk –

the mean and volatility of its bid-ask spread (and other measures of liquidity such as market depth) are an order of magnitude larger than their counterparts in the bond futures market. This imposes a clear limit to the arbitrage mechanism between the cash and futures markets in Italian sovereign bonds, since the arbitrage process is somewhat risky due to the difficulty of executing both legs of the cash-futures trade simultaneously. This is an important constraint on the smooth spillover of liquidity from one market to another that one would expect in markets linked by arbitrage.

Finally, we show that the ECB intervention through the LTRO had a clear effect on the arbitrage relationship, fostering the convergence of the basis to zero, and significantly reducing the response time in the lead-lag relationship between the cash and futures markets. Hence, the monetary policy intervention was useful not just in calming down the fears of the market and reducing the market's perception of credit risk, as documented in Pelizzon et al. (2014), but also in relaxing the limits to arbitrage and facilitating liquidity discovery between the cash and futures markets in Italian sovereign bonds. Our analysis has important policy implications for measuring and dealing with market liquidity, such as how to assess the impact of the Euro-zone crisis on the cash and futures markets in sovereign bonds, as well as the impact of central bank interventions. More generally, our study has lessons for the implications of monetary policy on market liquidity and price transmission, in the context of the underlying market microstructure. Specifically, we show that open-market asset-repurchase actions, such as the SMP, OMT, and LTRO, have an impact on the liquidity of the interdealer market for government bonds, which is then transmitted to the futures market through arbitrage. Understanding how the liquidity in the two markets interacts, and how price discovery takes place, is pivotal to the efficient tailoring of such open-market operations, especially since massive central bank operations, particularly in the context of quantitative easing, are bound to substantially affect liquidity. Central banks may also learn from our analysis, in that it could help them better understand the impact of the new unconventional instruments of monetary policy on the markets, and how they can be improved, possibly by including the usage of the futures markets as one of their intervention tools. For market regulators, the presence of arbitrage opportunities between two markets that should, in theory, be perfectly aligned is a matter of concern. The identification of the sources of such limits to arbitrage is the first step towards ensuring the efficient transmission of central bank actions to the marketplace. Finally, our work should be of interest to national treasuries, helping them to understand the dynamic nature of the relationship between market liquidity in the cash and futures markets, which has strong consequences for the pricing of their sovereign debt issues in the auctions. Similarly, market participants, such as market makers and arbitrageurs, would benefit from understanding the linkages between monetary policy interventions and the liquidity in the sovereign bond cash and futures markets.

Appendix A

Calculating the net basis

In order to determine which bond is the CTD, we calculate the net basis, which represents the mispricing in euros between the two securities. While the *gross basis*, which is calculated as $F_{it} - P_{it} \cdot CF_i$, is a first approximation of the profit a trader can expect to safely lock in, it assumes that the trader either owns or will buy the bond i at the current price P_{it} and hold onto it until delivery, without considering its opportunity cost.

A more precise and careful estimation of the profit that an arbitrageur is actually going to gain is the *net basis*, which takes into account that an arbitrageur would likely reverse-repo the bond, and that any bond transaction entails the exchange of accrued interest. The quantity in the gross basis formula which is affected by these considerations is P_{it}, which is substituted by $FP_{it,T}$, the forward T-price of bond i at time t, in the net basis. The forward price takes into account that i) when the arbitrageur purchases the bond at time t, she would have to pay the coupon accrued from the previous coupon date (or the issue date) on top of the market price P_{it} ii) the arbitrageurs would pay a repo-rate as compensation for borrowing the bond from the day she enters this position to the delivery rate and iii) at delivery, the trader with the long position in the futures would compensate that with the short position for the coupon accrued until delivery.

The forward price for bond i at time t with delivery at date T is thus calculated as

$$FP_{i,t,T} = (P_{i,t} + AC_{i,t+2}) \cdot \left(1 + \frac{T-(t+2)}{360} r_t\right) - AC_{i,T} \tag{9}$$

where $\frac{T-(t+2)}{360} r_t$ is the length of the repo, considering a $t+2$ settlement for the underlying bond, multiplied by the repo rate at time t, $AC_{i,t+2}$ is the coupon accrued from the last payment before settlement until the trade settlement date, and $AC_{i,T}$ is the coupon accrued from the last payment before settlemen until delivery. Coupon accrual is calculated using the ACT/ACT convention, while the repo is based on the ACT/360 convention.

In our sample period, all CTD bond are also the on-the-run 10 years bonds, which poses another issue in calculating the accrued coupon. While for a regular coupon the first coupon date is exactly six months since the issue date, as the coupon payment is biannual, some bonds issued by the Italian Treasury pay the first coupon less than six months from issuance. If that is the case, a odd-sized coupon is payed on the first coupon date and its amount can be calculated as $\frac{FC-ID}{FC-PC}\frac{c}{2}$, where FC is the first coupon date, ID is the issue date, and PC is the date of the coupon that would have been payed before issuance, i.e. six months before the first coupon date. Notice that also this calculation follows the ACT/ACT convention. If a short-first bond is traded in the secondary market before the first coupon date, the accrued coupon will be calculated as a fraction of the odd-sized coupon, namely a trade with settlement date SD ($SD < FC$) will entail an accrued coupon equal to $\frac{SD-ID}{FC-ID}\frac{FC-ID}{FC-PC}\frac{c}{2}$.

The quality option in the BTP futures market

The quality option implies that the agent with the short position in the BTP futures contract (and other Treasury bond futures contracts) has an optionality that may be valuable. The source of this optionality is that the short position has the right to physically deliver any one of a set of bonds into the futures contract. The credit received for such deliver depends on the conversion factors used in the calculations above: In the case of the BTP futures contract, these are presently computed using a 6% yield and a 6% coupon. Clearly, if all the candidate bonds had a 6% coupon, and the yield curve was flat at 6%, and is expected to stay that way, all bonds would be equally cheap to deliver and the option would have no value. If the yield curve is flat at a higher yield than 6%, all bonds would go down in price and the CTD bond would be the one that goes down the most, i.e., the one with the longest duration. Similarly, if the yield curve is flat at a yield below 6%, the shortest duration bond would be the CTD. If the yield curve is not flat, the calculations would be someone more complex, but the essentially argument would be similar.

The complicating factor in the above analysis is that the bond that is currently CTD, will not remain so, if the yield curve shifts. This becomes a relevant issue, when the yield curve is around 6%. In the BTP market, during most of our period of analysis, the yields were much lower than 6%, and hence the option was deep out of the money. (This is also true for most Treasury bond futures markets today, in a regime of unusually low long-term interest rates.) However, at the peak of the crisis, particularly between June 2011 and January 2012, the yields were above this level for several days. At this point, the option may have been valuable. The question is how valuable. Prior calculations in other markets suggests that the option was work between 20 and 30 bps, on average (Hemler, 1990). In recent years, this has not been an issue in the US T Bond futures market or the German Bund futures market, since the option has been worth very little.

There is a few important differences between the BTP market and other Treasury markets. First, the Italian Tesoro often issues the same bond again, rather than initiating a new series. The result is that the number of candidate bonds that are deliverable into the BTP futures contract is much smaller than, for example, the US T Bond market. Second, during most of our sample period, the difference between the basis between the futures contract and the CTD bond, and the basis with respect to the next cheapest bond, is very small. Cite some numbers. Hence, even if the value of the CTD option was around 20-30 bps, in line with the numbers in other markets, it would hardly have caused the CTD to change. Third, we observe only one short-lived switch in our sample period. Indeed, the on-the-run bond is almost always the CTD bond. For all these reasons, the value of the option ex post, was negligible. While this does not prove that the option was worth very little ex ante, it is unlikely that the market did not anticipate this and take it into account ex ante. We conclude, therefore, that ignoring the value of the CTD option would not make much of difference to our analysis.

Tables

Table I
Descriptive Statistics I.

This table presents summary statistics for liquidity measures common to both cash and futures markets, distinguishing between on-the-run 10-year bonds and BTP futures. Descriptive statistics of quote- and trade-based liquidity measures. Quoted (percent) bid-ask spread: time-weighted difference between best bid and ask divided by mid-price of best ask and bid. Depth: quantity available at best ask (or bid) in euros. Quote revisions: number of quote revisions including the changes in ask, bid, and their quantity. Number of trades: number of trades filled, on the European and/or domestic market. Volume: traded volume on the European and/or domestic market, aggregated in terms of notional euro amount of bonds. Trade imbalance: number of buyer-initiated trades minus number of seller-initiated trades. In the case of MTS transactions, the side of the orders is provided. In the case of BTP futures, we use Lee and Ready's (1991) method to separate buy and sell. We do not include trades with prices equal to the mid-price of the prevailing quotes. Volume imbalance: Volume of buyer-initiated trades minus that of seller-initiated trades, in euros. All stats are computed as follows: first, we take the time-weighted average over a day; then, we compute an average over the entire period. In the case of deliverable bonds, we compute the daily average of the individual bond and then we compute the average for the day. The data are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

	On-the-run 10 year BTP			**BTP futures**		
Measures	Average	Median	St.Dev	Average	Median	St.Dev
Quoted Spread						
Bid-Ask Spread	0.307%	0.235%	0.234%	0.036%	0.033%	0.023%
Depth						
Depth at Best Ask (Million Euro)	8.350	7.840	3.180	7.150	6.500	2.180
Depth at Best Bid (Million Euro)	7.540	7.020	2.810	7.120	6.470	2.520
Quote Revisions per Day	7597.400	6679.000	5561.500	10 594.500	9284.500	6361.000
Trading Activities						
Total Number of Trades	23.400	16.000	26.600	3788.000	3448.000	2411.000
Buyer-initiated Trades	11.400	6.000	15.400	1840.000	1696.000	1174.000
Seller-initiated Trades	12.000	8.000	14.900	1878.000	1723.000	1203.000
Total Volume (Million Euro)	107.600	64.500	131.500	1288.200	1175.300	749.800
Buyer-initiated Volume	51.400	24.500	74.700	630.900	572.000	382.200
Seller-initiated Volume	56.200	30.000	77.800	638.500	573.300	363.400
Absolute Trade Imbalance(%)	49.700%	47.400%	32.600%	5.700%	4.600%	5.000%
Positive Imbalance	49.400%	50.000%	34.500%	6.200%	5.100%	5.500%
Negative Imbalance	50.000%	46.700%	31.000%	5.100%	4.200%	4.200%
Absolute Volume Imbalance (%)	53.000%	51.600%	32.500%	7.600%	6.300%	6.100%
Positive Imbalance	52.200%	51.300%	34.100%	8.000%	6.500%	6.400%
Negative Imbalance	53.700%	53.600%	31.000%	7.300%	6.000%	5.800%

Table II

Descriptive Statistics II.

This table presents the distributions of the main variables we consider in the analysis, separately for the bonds and futures markets. The futures contract we consider at any point in time is the long-term futures on the Italian government bonds with closest delivery date. The bond we consider is the cheapest-to-deliver of the underlying 10-year bonds. The variables are standard, namely the bid-ask spread, the price and yield (for the bonds), the coupon rate and the duration (in years). Lambda is the expected change in the bid or ask price following a large trade. All variables are described in Section III. The data are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

Bond Market						
	Five-minute Intervals			Daily Data		
Variable	Mean	Median	SD	Mean	Median	SD
Price	97.341	97.865	6.009	97.350	97.822	6.017
Bid-Ask Spread	0.254	0.190	0.237	0.259	0.203	0.196
λ^A	0.016	0.008	0.047	0.017	0.011	0.024
λ^B	0.017	0.008	0.044	0.018	0.012	0.030
$\lambda^A - \lambda^B$	−0.001	0.000	0.046	−0.001	−0.001	0.017
Futures Market						
	Five-minute Intervals			Daily Data		
Variable	Mean	Median	SD	Mean	Median	SD
Price	101.878	101.565	5.325	101.887	101.571	5.326
Bid-Ask Spread	0.034	0.030	0.020	0.034	0.033	0.010

Table III

Co-Integration Analysis.

This table presents the results for the co-integration analysis of the futures and bond price series, where the bond considered is the cheapest-to-deliver for the relative long-term futures contract. Panel A shows the rank tests, Panel B shows the β and α vectors, normalized at 1 for the bond price, and Panel C presents the short-term adjustment coefficients. The co-integration system is defined in Equation 1. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

Panel A

H_0	H_1	Trace Test (Five-minute)	Trace Test (Daily)	5% Value
Rank=0	Rank>0	46.450	24.860	19.990
Rank=1	Rank>1	1.840	1.430	9.130

Panel B

	Five-minute		Daily	
	The β Vector	The α Vector	The β Vector	The α Vector
Futures Price	−1.003	−0.000	−1.005	−0.085
Bond Price	1.000	−0.005	1.000	−0.193
Constant	−0.497		−0.286	

Panel C

		Five-minute		Daily
Equation	Lagged ΔVariable	Significant Lags	Of Which Positive	Lagged ΔVariable
Futures Price	Futures Price	1 of 5	0 of 1	No Lags Selected
	Bond Price	3 of 5	3 of 3	No Lags Selected
Bond Price	Futures Price	5 of 5	0 of 5	No Lags Selected
	Bond Price	5 of 5	5 of 5	No Lags Selected

Table IV
Wald Test Results.

This table shows the results of the Wald test for the contemporaneous statistical insignificance of the lags of the row-variable in the column-variable equation. The VAR system considered is that defined by Equation 3. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012. $*$, $**$, and $***$ indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

	Five-minute			Daily		
Causing/Caused	Basis	Bid-Ask Bond	Bid-Ask Futures	Basis	Bid-Ask Bond	Bid-Ask Futures
Basis	155.650***	21.920	13.280	2527.740***	3.040	0.720
Bid-Ask Bond	13.420	138.890***	11.880	12.010**	38.140***	17.240***
Bid-Ask Future	14.160	19.410	12 392.590***	2.560	6.840	220.020***

Table V
Wald Test Results.

This table shows the results of the Wald test for the contemporaneous statistical insignificance of the lags of the row-variable in the column-variable equation. The VAR system considered is that defined by Equation 4. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012. $*$, $**$, and $***$ indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Causing/Caused	Basis	λ^{ASK}	λ^{BID}	Bid-Ask Futures
Basis	456.180***	26.880**	23.010	17.320
λ^{ASK}	26.270*	326.430***	21.320	21.270
λ^{BID}	23.740*	52.260***	80.120***	32.580***
Bid-Ask Future	21.000	24.170*	20.360	12 375.130***

Table VI
Wald Test Results.

This table shows the results of the Wald test for the contemporaneous statistical insignificance of the lags of the row-variable in the column-variable equation. The VAR system considered is that defined by Equation 7. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012. $*$, $**$, and $***$ indicate a statistical significance at the 10%, 5%, and 1% level, respectively.

Causing/Caused	Basis	$\lambda^{ASK} - \lambda^{BID}$	Bid-Ask Futures
Basis	450.000***	21.350	17.450
$\lambda^{ASK} - \lambda^{BID}$	27.860**	79.460***	30.120**
Bid-Ask Future	20.580	15.020	12 367.410***

Figures

Figure 1
The Futures-Bond Basis for Different Bonds.

This figure shows the time-series evolution of the net basis in euros, as defined in Equation 8, for all the deliverable bonds and all the delivery dates. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

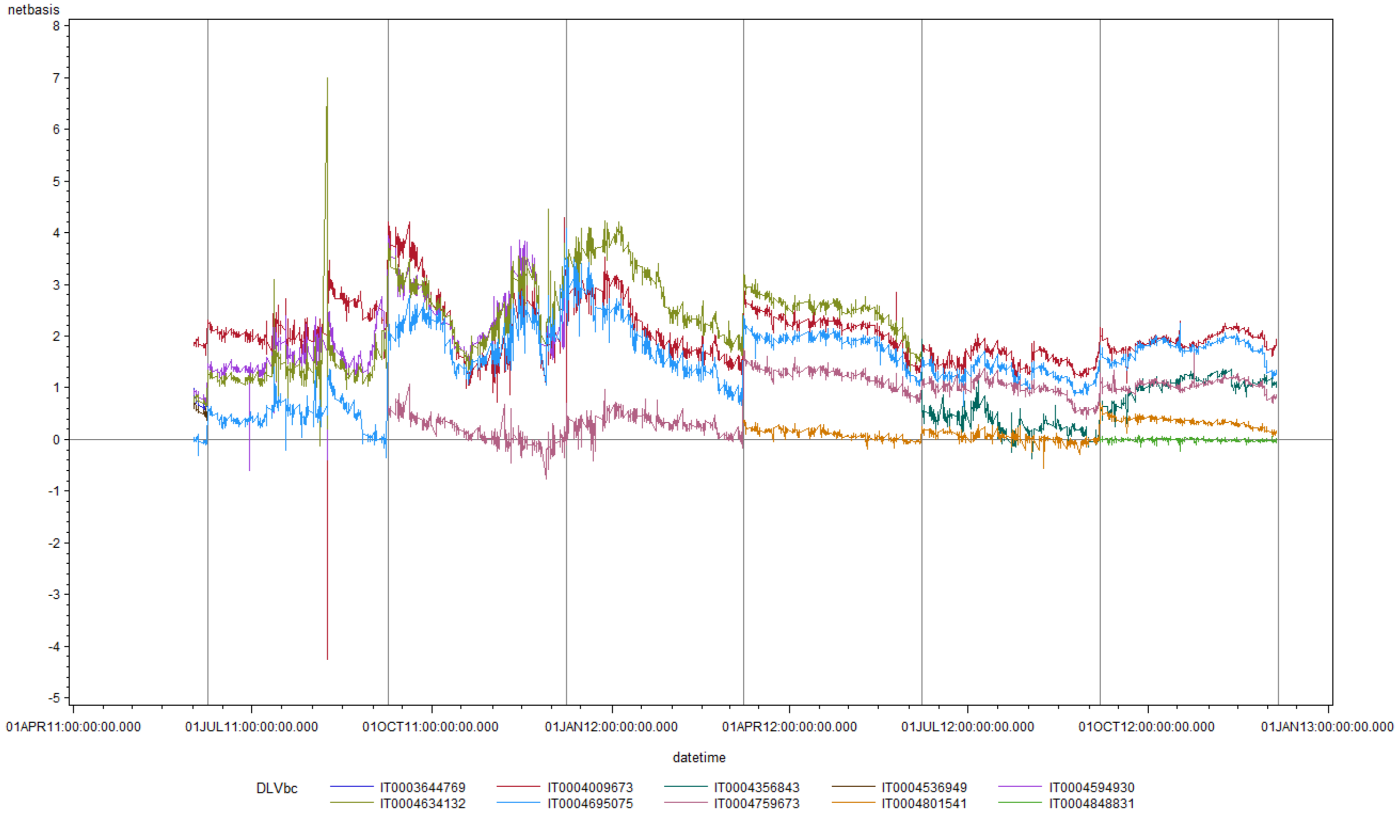


Figure 2
The Futures-Bond Basis for the CTD.

This figure shows the time-series evolution of the net basis in euros, as defined in Equation 8, for the bond that is the cheapest-to-deliver and for all the delivery dates.The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

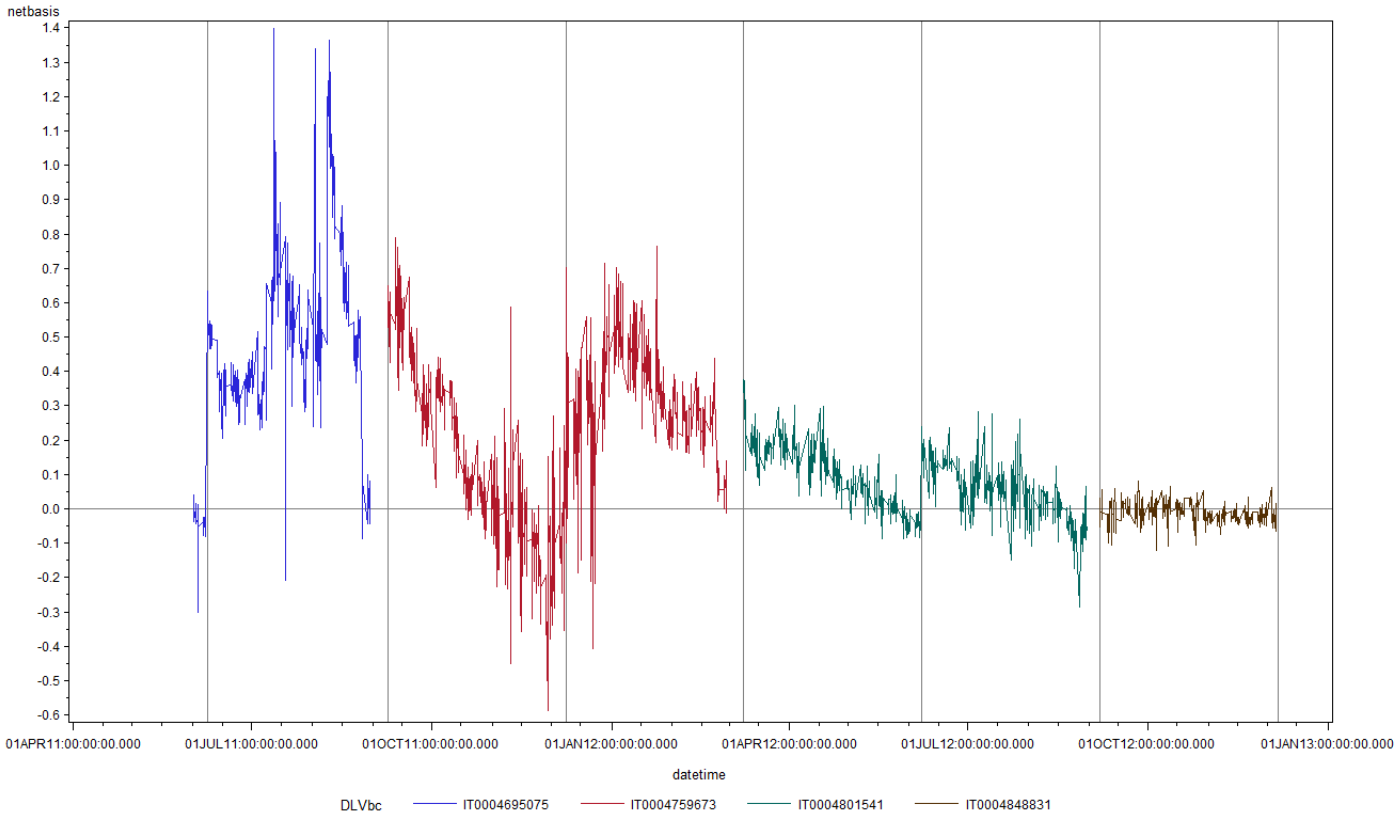


Figure 3
The Price of the CTD Bond and Scaled Futures.

This figure shows the time-series evolution of the CTD bond and corresponding conversion factor-adjusted futures price in euros. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

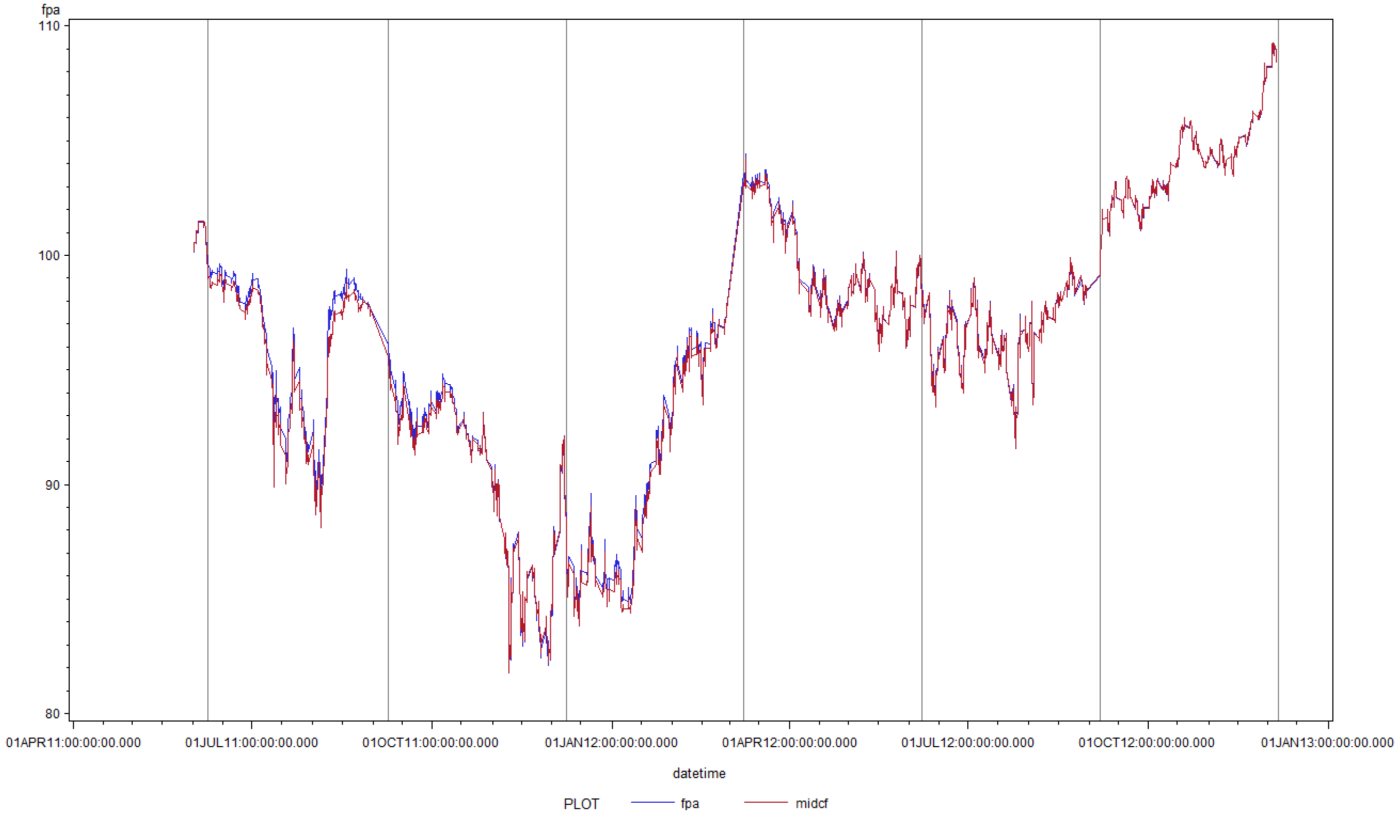
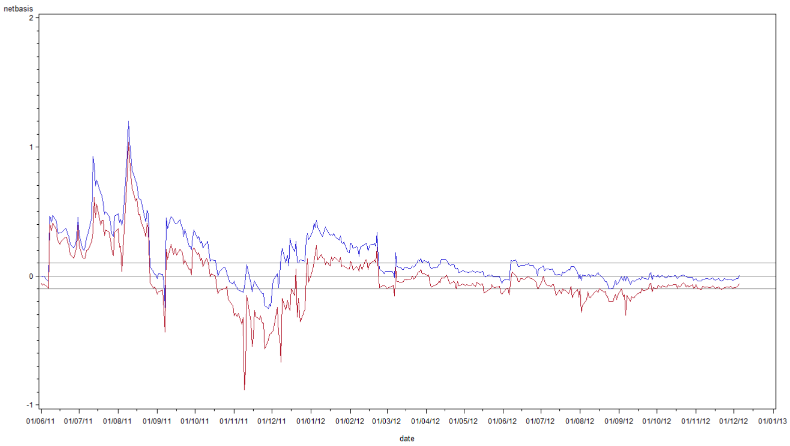


Figure 4
The Price of the CTD Bond and Scaled Futures.

This figure shows the time-series evolution of the basis between futures and CTD bond, based on midquotes and bid/ask quotes. Panel A shows the midquote basis in blue and the buy futures/short bond basis in red. Panel B shows the executable basis of the buy futures/short bonds and the sell futures/buy bonds strategies, in blue and red, respectively. The data have a daily frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

A: Basis and Executable Basis



B: Executable Bases

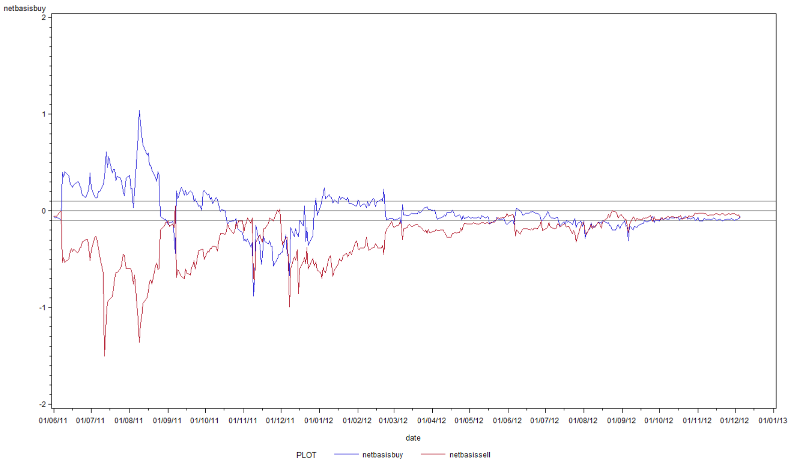


Figure 5
The Bid-Ask Spreads of the CTD Bond and Futures.

This figure shows the time-series evolution of the bid-ask spread for the CTD bond (left axis, in euros) and corresponding futures price (right axis, in euros).The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

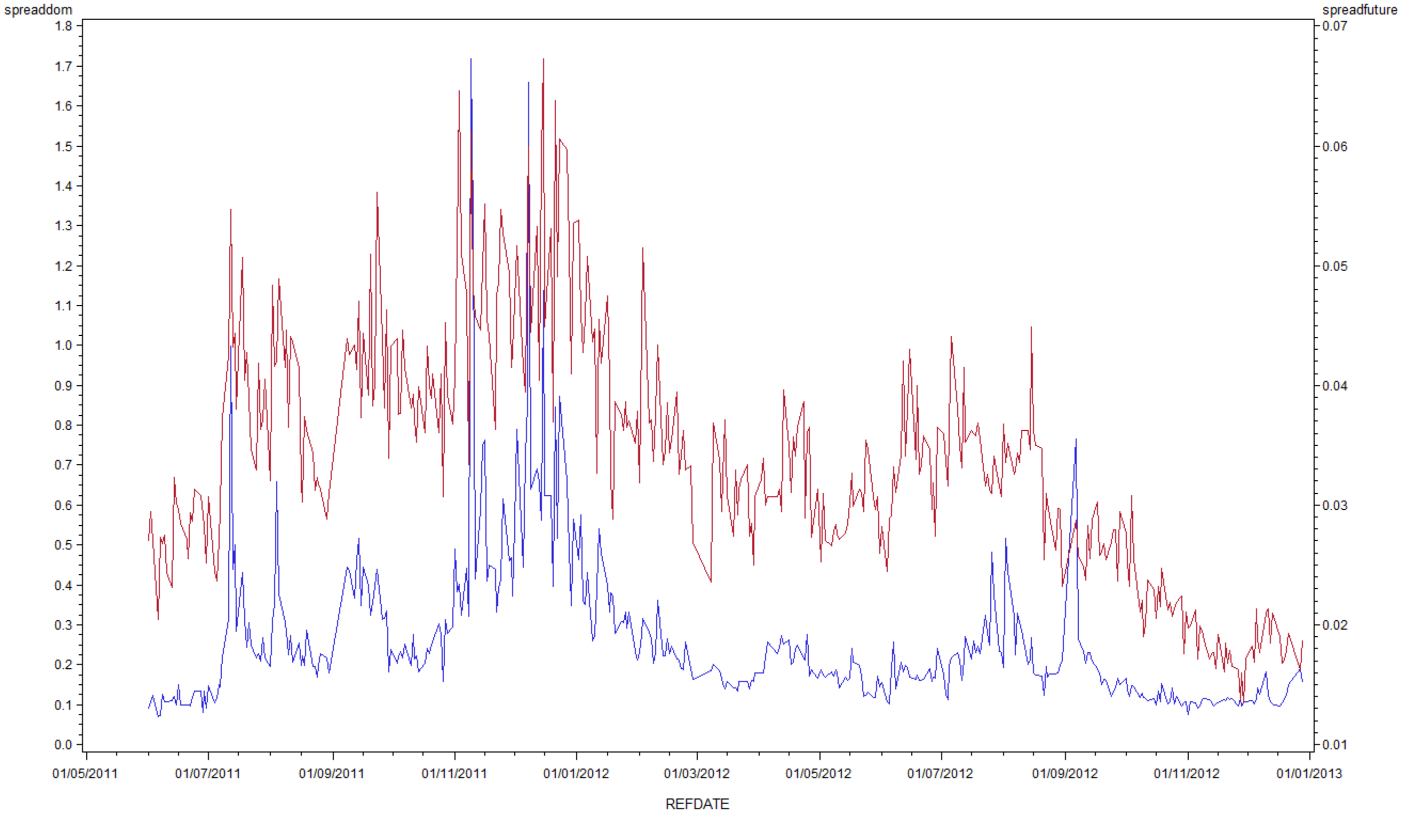


Figure 6
The λ^A and λ^B Measures.

This figure shows the time-series evolution of the λ measures for the bond market. The measures are defined in Section III. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

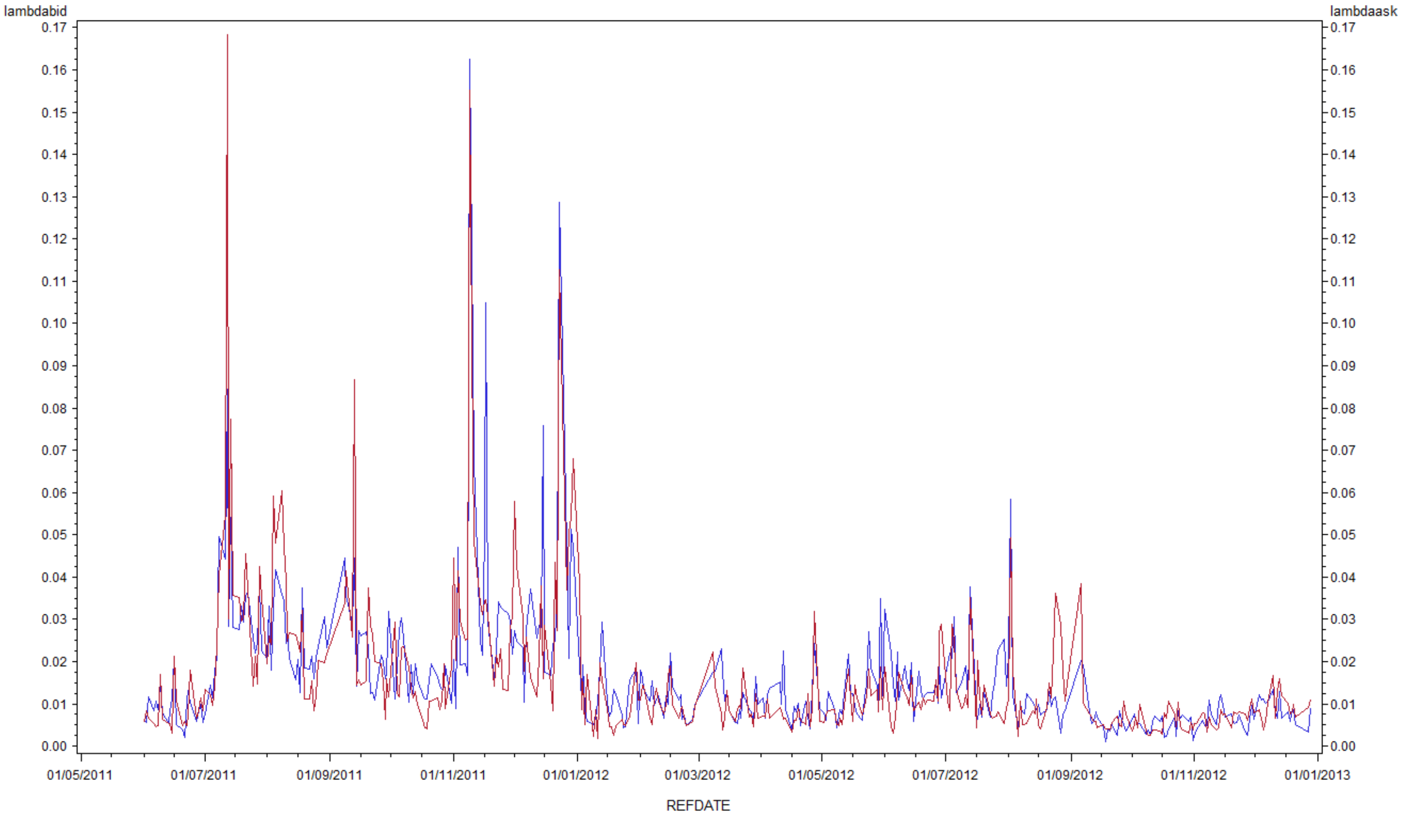


Figure 7
The $\lambda^A - \lambda^B$ Measure.

This figure shows the time-series evolution of the difference between the λ measures for the bond market. The measures are defined in Section III. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

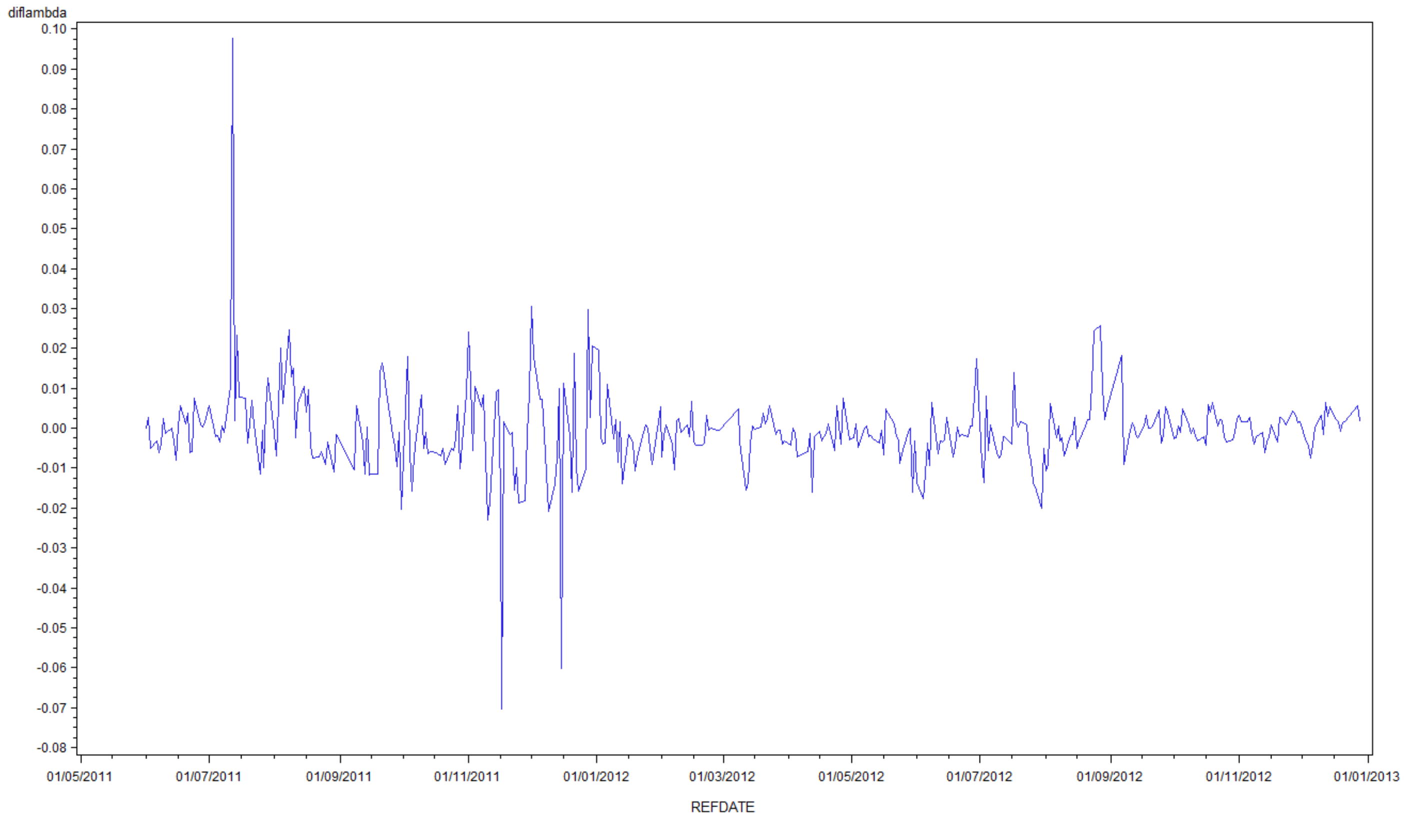
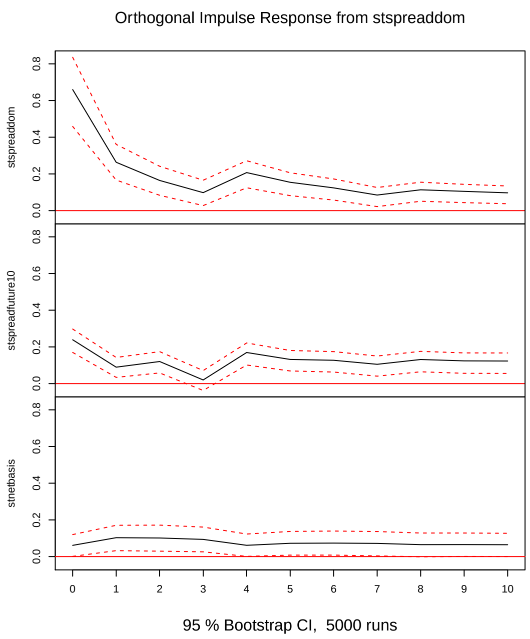


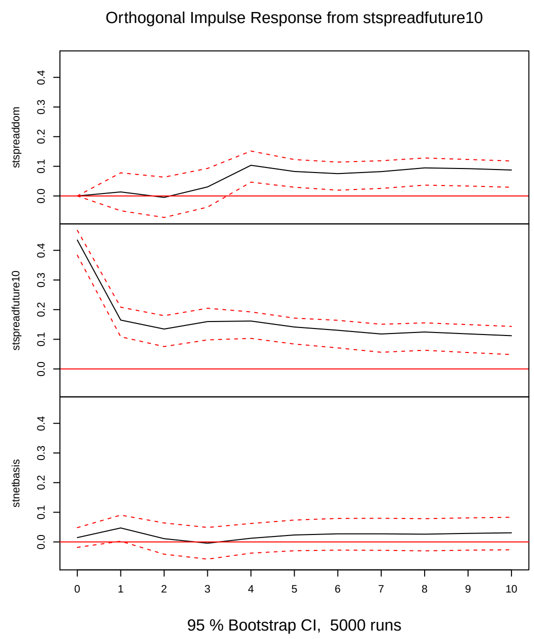
Figure 8
Simple Impulse Response Functions.

This figure shows the orthogonal impulse response functions to a shock to the system variables. The variables were re-sized to have an average of 0 and a standard deviation of 1, hence the Y-axis measures changes as proportions of a unit-standard deviation. The corresponding VAR uses daily data, and the confidence bands were obtained by bootstrap.

A: Responses to a Shock to Bond Liquidity



B: Responses to a Shock to Futures Liquidity



C: Responses to a Shock to Net Basis

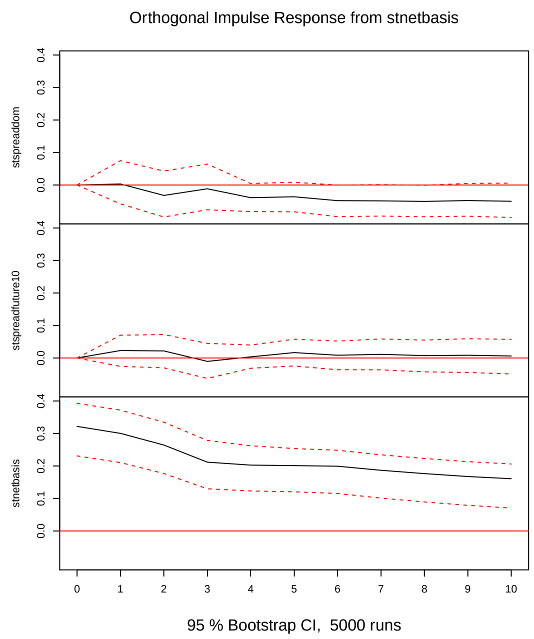
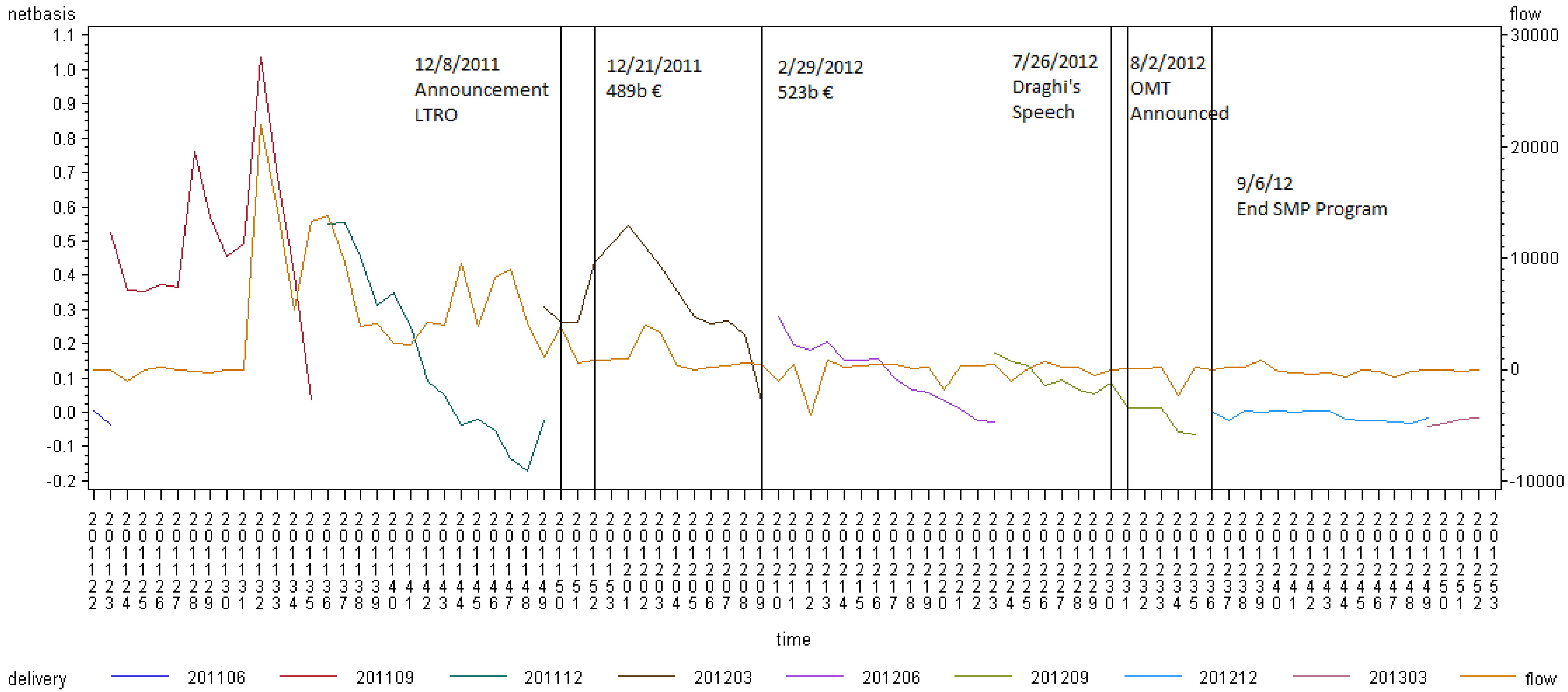


Figure 9
Basis and ECB Interventions.

This figure shows the time-series evolution of the net basis between futures and bond (left axis), and the flow amount of European sovereign bonds that were purchase by the ECB in the context of the SMP intervention. The data are at a weekly frequency. Our sample period is June 2011 to December 2012.



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