Limits to Arbitrage in Sovereign Bonds

Price and Liquidity Discovery in High-Frequency Quote-Driven Markets *

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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.

Keywords: Liquidity, government bonds, futures markets, futures-bond basis, arbitrage.

JEL Classification: G01, G12, G14.

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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, while the descriptive statistics are presented in Section V. The empirical results are presented in Section VI and Section VII 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 et al (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 (1996), 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 et al. (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 et al. (2000) and Chordia et al. (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. (2010) 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 et al.

(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. Brokman 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 et al. (2012) and Mancini et al. (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 at al. (1989) and Roll et al. (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 (2009), Nashikkar et al. (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.I 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]

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

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

delivery day of the relevant maturity month.

III.II 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 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 et al. (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

[2]See also Dufour and Skinner (2004) and Pelizzon et al. (2014).

[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.

side of 96% of the trades present in our database.[5]

III.III 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* attempts to combine the two previous proxies by measuring 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 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.IV 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 1 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

[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. (2014).

[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 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.

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 1 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).

The average number of daily quote revisions of the on-the-run bond and the futures contract are 7,597 and 10,595, 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.I 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.II 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.III 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.

$$\begin{aligned}
\Delta\lambda_t^A =& \alpha + \sum_{i=1}^{p} \beta_i^A \Delta\lambda_{t-i}^A + \sum_{i=1}^{p} \beta_i^B \Delta\lambda_{t-i}^B + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i} \\
\Delta\lambda_t^B =& \alpha + \sum_{i=1}^{p} \beta_i^A \Delta\lambda_{t-i}^A + \sum_{i=1}^{p} \beta_i^B \Delta\lambda_{t-i}^B + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i} \\
\Delta QS_{fut,t} =& \alpha + \sum_{i=1}^{p} \beta_i^A \Delta\lambda_{t-i}^A + \sum_{i=1}^{p} \beta_i^B \Delta\lambda_{t-i}^B + \sum_{i=1}^{p} \gamma_i \Delta QS_{future,t-i} + \sum_{i=1}^{p} \delta_i \Delta B_{t-i}
\end{aligned} \tag{4}$$

IV.IV 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:

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

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

IV.V ECB Intervention

Pelizzon et al. (2014) 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. (2014) and re-estimate our model for the two samples separately.

IV.VI 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.I 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 $FP(i,t)$ 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 AND 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

[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.

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 2 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 FIGURE 6 AND 7 AND TABLE 2 HERE

V.II 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 3 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 3 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.III 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 4 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 4 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 4 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 4 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 4 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.II, 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.

V.III.1 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 5. 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 5 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 6. 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 6 HERE

V.IV 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

[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 2. 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

behavior, in turn the basis, and therefore the market liquidity of these two markets. When we look at the daily analysis that is based on levels, Table 4 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 4 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 5 and 6, 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.V 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 ECBs 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 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

[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.

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 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,

[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.

[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."

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).

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 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

[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)

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 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

were not significant at conventional significance levels.

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 1: **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)	8.35	7.84	3.18	7.15	6.50	2.18
Depth at Best Bid (Million Euro)	7.54	7.02	2.81	7.12	6.47	2.52
Quote Revisions per Day	7,597.4	6,679.0	5,561.5	10,594.5	9,284.5	6,361.0
Trading Activities						
Total Number of Trades	23.4	16.0	26.6	3,788	3,448	2,411
Buyer-initiated Trades	11.4	6.0	15.4	1,840	1,696	1,174
Seller-initiated Trades	12.0	8.0	14.9	1,878	1,723	1,203
Total Volume (Million Euro)	107.6	64.5	131.5	1,288.2	1,175.3	749.8
Buyer-initiated Volume	51.4	24.5	74.7	630.9	572.0	382.2
Seller-initiated Volume	56.2	30.0	77.8	638.5	573.3	363.4
Absolute Trade Imbalance(%)	49.7%	47.4%	32.6%	5.7%	4.6%	5.0%
Positive Imbalance	49.4%	50.0%	34.5%	6.2%	5.1%	5.5%
Negative Imbalance	50.0%	46.7%	31.0%	5.1%	4.2%	4.2%
Absolute Volume Imbalance (%)	53.0%	51.6%	32.5%	7.6%	6.3%	6.1%
Positive Imbalance	52.2%	51.3%	34.1%	8.0%	6.5%	6.4%
Negative Imbalance	53.7%	53.6%	31.0%	7.3%	6.0%	5.8%

Table 2: **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	97.3406	97.8650	6.00901	97.3504	97.8224	6.01731
Bid-Ask Spread	0.2535	0.1900	0.23660	0.2585	0.2030	0.19624
λ^A	0.0158	0.0083	0.04714	0.0168	0.0105	0.02443
λ^B	0.0166	0.0083	0.04377	0.0179	0.0119	0.03033
$\lambda^A - \lambda^B$	-0.0010	0.0000	0.04574	-0.0014	-0.0013	0.01654
Futures Market						
	Five-minute Intervals			Daily Data		
Variable	Mean	Median	SD	Mean	Median	SD
Price	101.8778	101.5650	5.32480	101.8873	101.5706	5.32629
Bid-Ask Spread	0.0338	0.0300	0.01964	0.0338	0.0332	0.00992

Table 3: **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	46.45	24.86	19.99
Rank=1	Rank>1	1.84	1.43	9.13

Table 3: Co-Integration Analysis (continued)

Panel B				
	Five-minute		Daily	
	The β Vector	The α Vector	The β Vector	The α Vector
Futures Price	-1.00268	-0.00016	-1.00506	-0.08478
Bond Price	1	-0.00513	1	-0.19314
Constant	-0.49659		-0.28582	

Table 3: Co-Integration Analysis (continued)

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 4: **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.

	Five-minute			Daily		
Causing/Caused	Basis	Bid-Ask Bond	Bid-Ask Futures	Basis	Bid-Ask Bond	Bid-Ask Futures
Basis	155.65***	21.92	13.28	2527.74***	3.04	0.72
Bid-Ask Bond	13.42	138.89***	11.88	12.01**	38.14***	17.24***
Bid-Ask Future	14.16	19.41	12392.59***	2.56	6.84	220.02***

Table 5: **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.

Causing/Caused	Basis	λ^{ASK}	λ^{BID}	Bid-Ask Futures
Basis	456.18***	26.88**	23.01	17.32
λ^{ASK}	26.27*	326.43***	21.32	21.27
λ^{BID}	23.74*	52.26***	80.12***	32.58***
Bid-Ask Future	21.00	24.17*	20.36	12375.13***

Table 6: **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.

Causing/Caused	Basis	$\lambda^{ASK} - \lambda^{BID}$	Bid-Ask Futures
Basis	450***	21.35	17.45
$\lambda^{ASK} - \lambda^{BID}$	27.86**	79.46***	30.12**
Bid-Ask Future	20.58	15.02	12367.41***

Table 7: **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 2011 in Panel A, and January 2012 to December 2012 in Panel B.

Panel A: 2011			
Causing/Caused	Basis	$\lambda^{ASK} - \lambda^{BID}$	Bid-Ask Futures
Basis	270.85***	21.98	20.13
$\lambda^{ASK} - \lambda^{BID}$	32.7***	533.13***	28.17**
Bid-Ask Futures	17.36	18.42	2710.61
Panel B: 2012			
Causing/Caused	Basis	$\lambda^{ASK} - \lambda^{BID}$	Bid-Ask Futures
Basis	1101.5***	18.99	15.42
$\lambda^{ASK} - \lambda^{BID}$	20.25	288.23***	19.59
Bid-Ask Futures	20.28	14.67	9315.89***

Figures

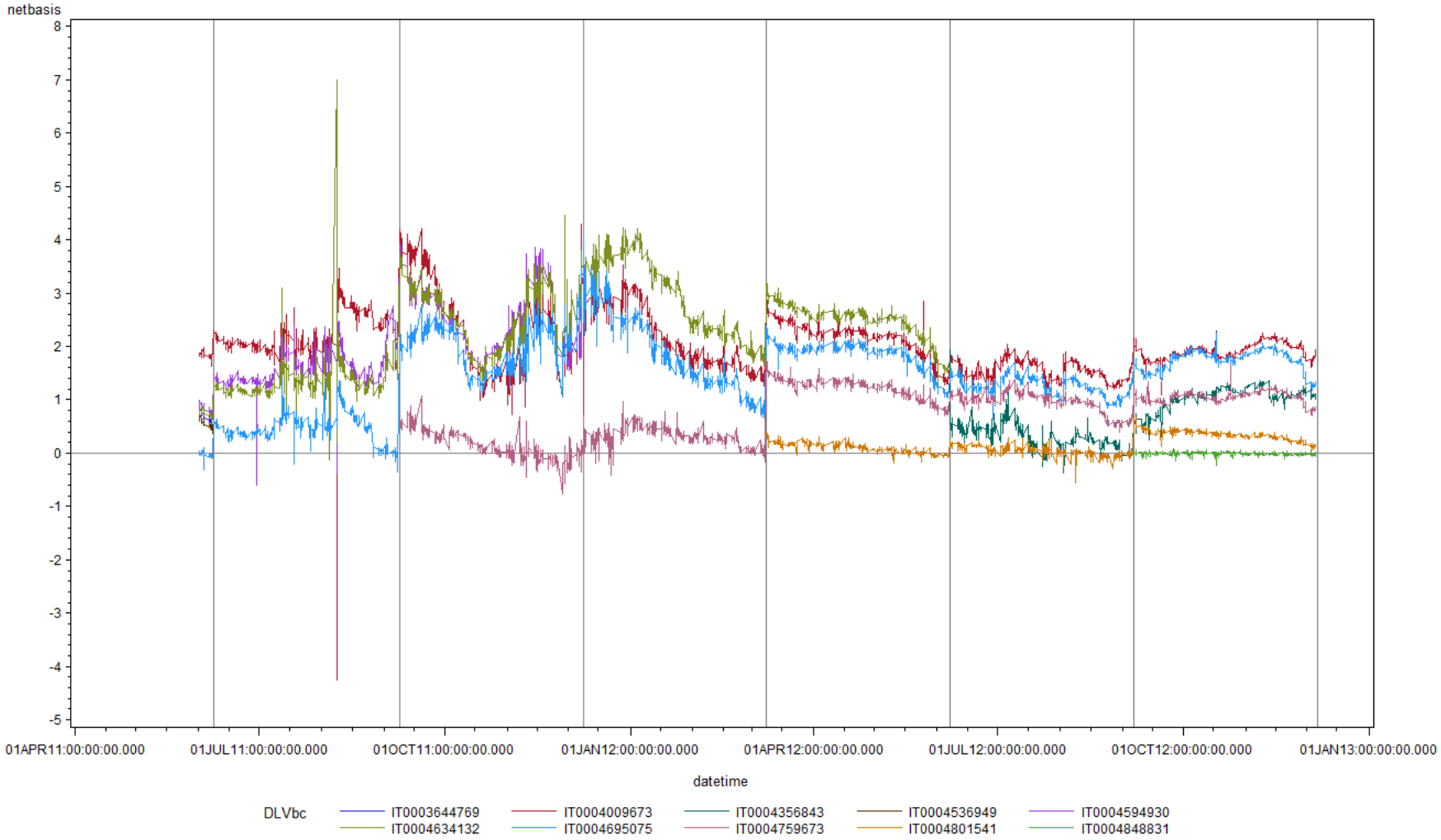


Figure 1: **The Futures-Bond Basis for Different Bonds:** This figure shows the time-series evolution of the net basis in euros, as defined in Equation 8, for all the deliverable bonds and all the delivery dates. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

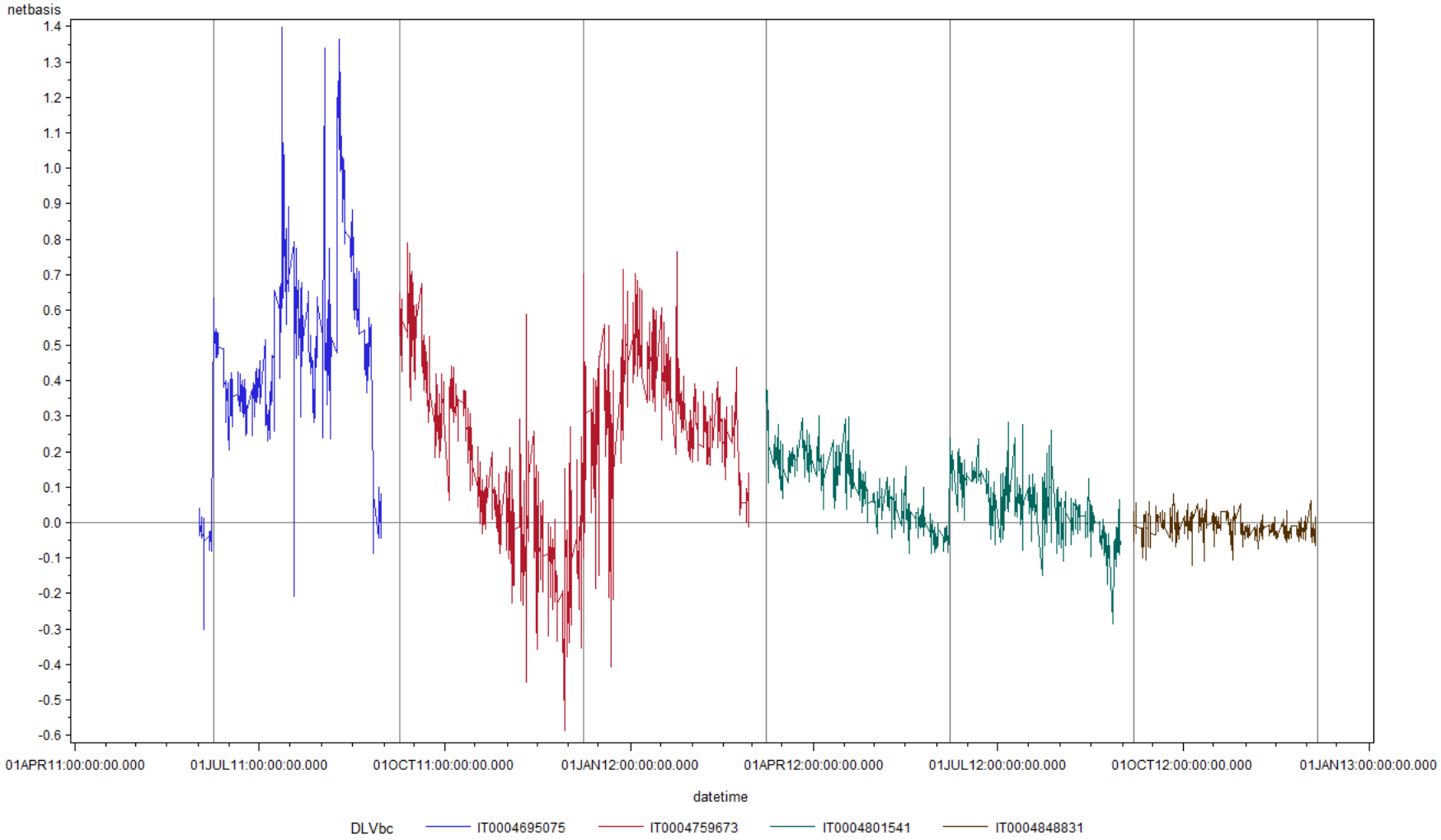


Figure 2: **The Futures-Bond Basis for the CTD:** This figure shows the time-series evolution of the net basis in euros, as defined in Equation 8, for the bond that is the cheapest-to-deliver and for all the delivery dates.The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

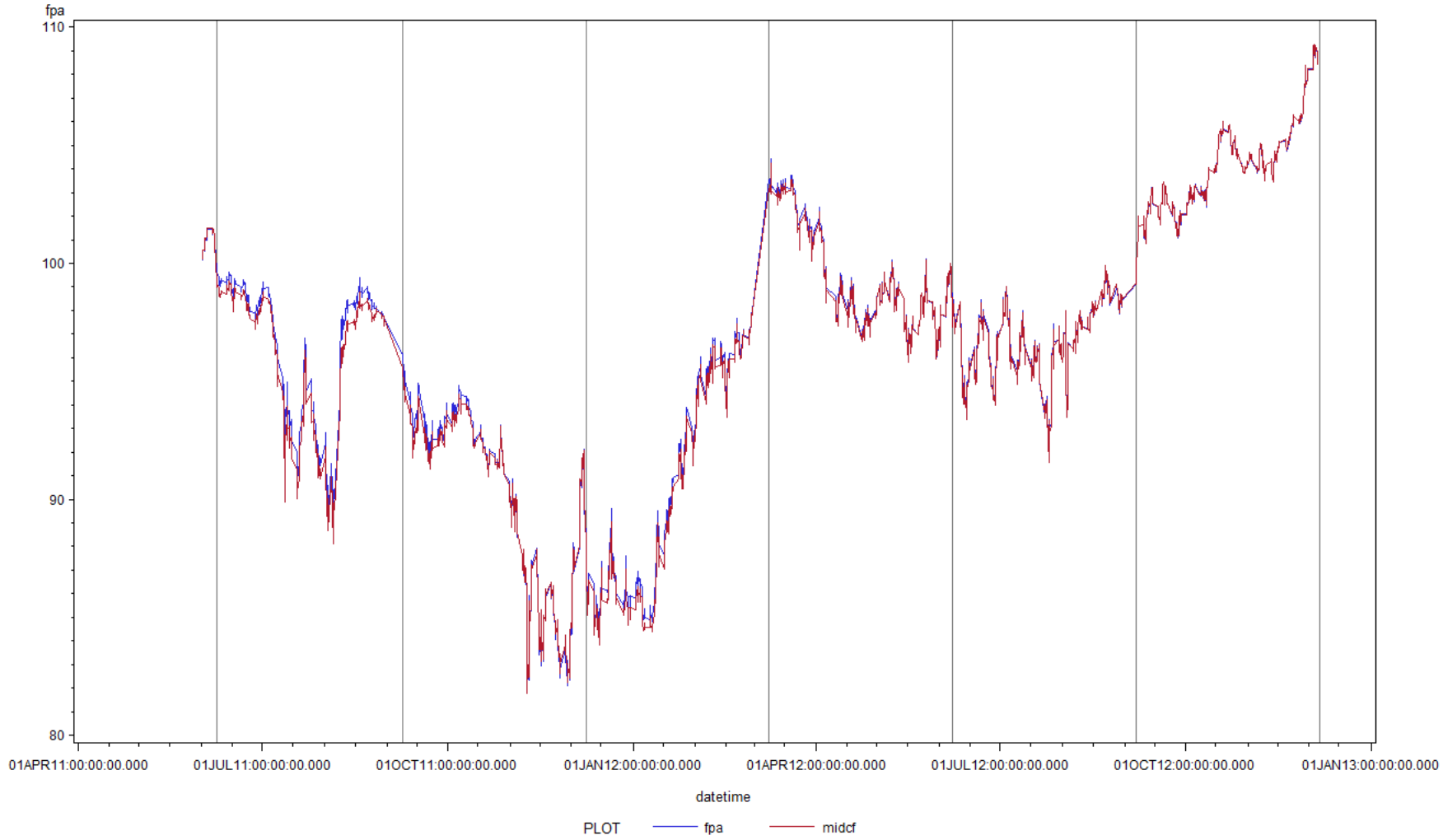
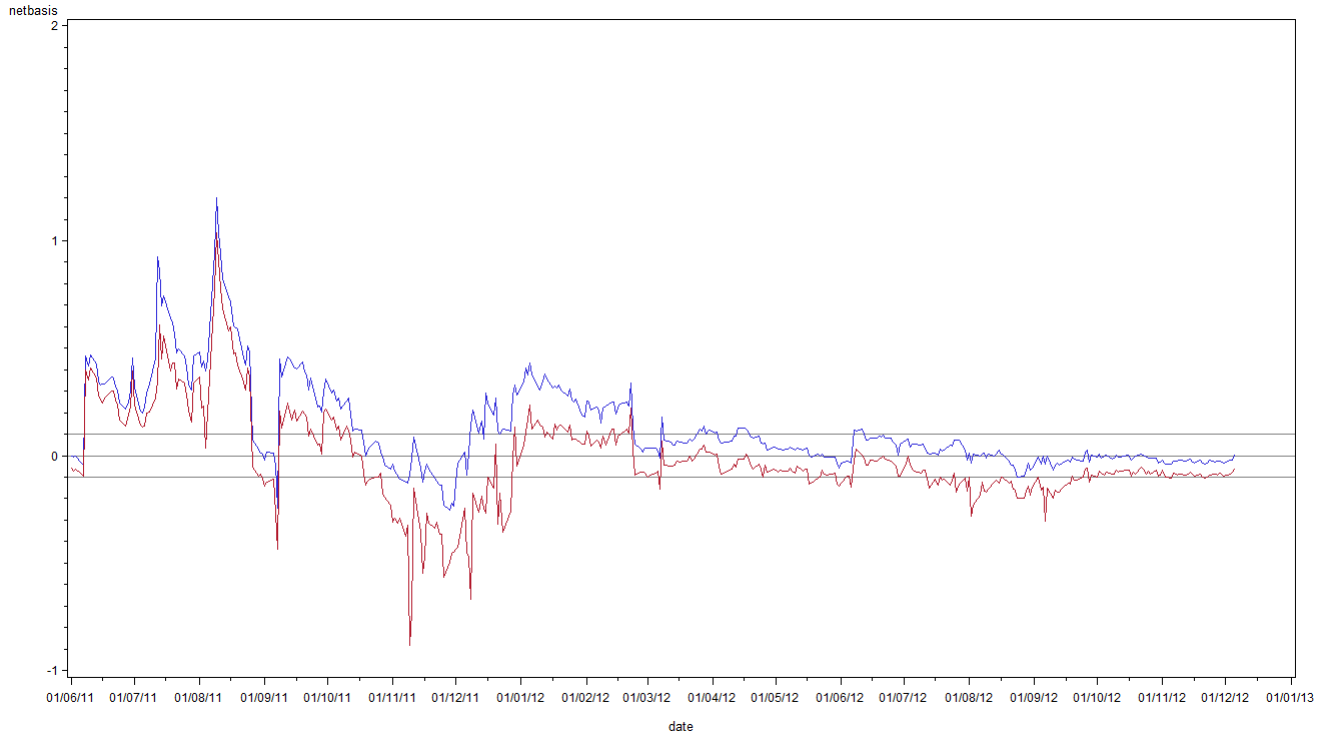
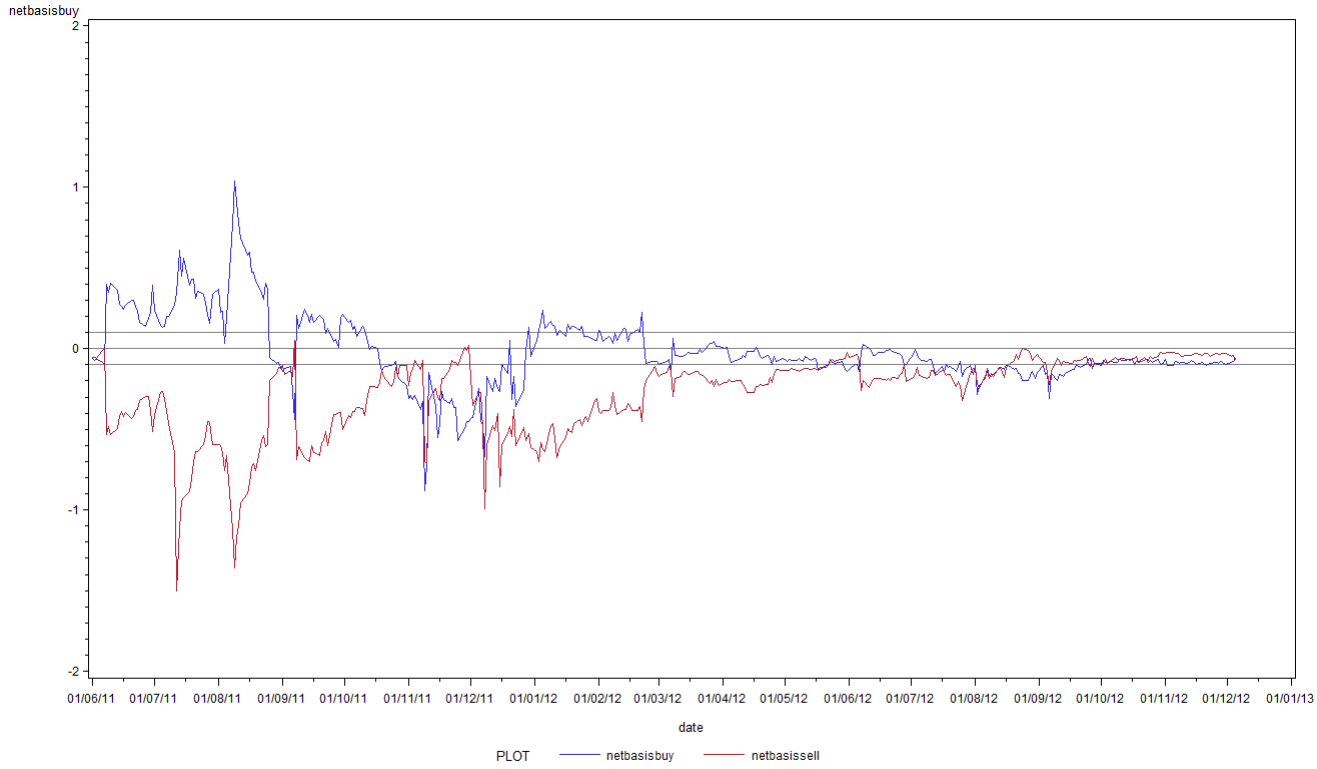


Figure 3: **The Price of the CTD Bond and Scaled Futures:** This figure shows the time-series evolution of the CTD bond and corresponding conversion factor-adjusted futures price in euros. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.



(a) Basis and Executable Basis



(b) Executable Bases

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.

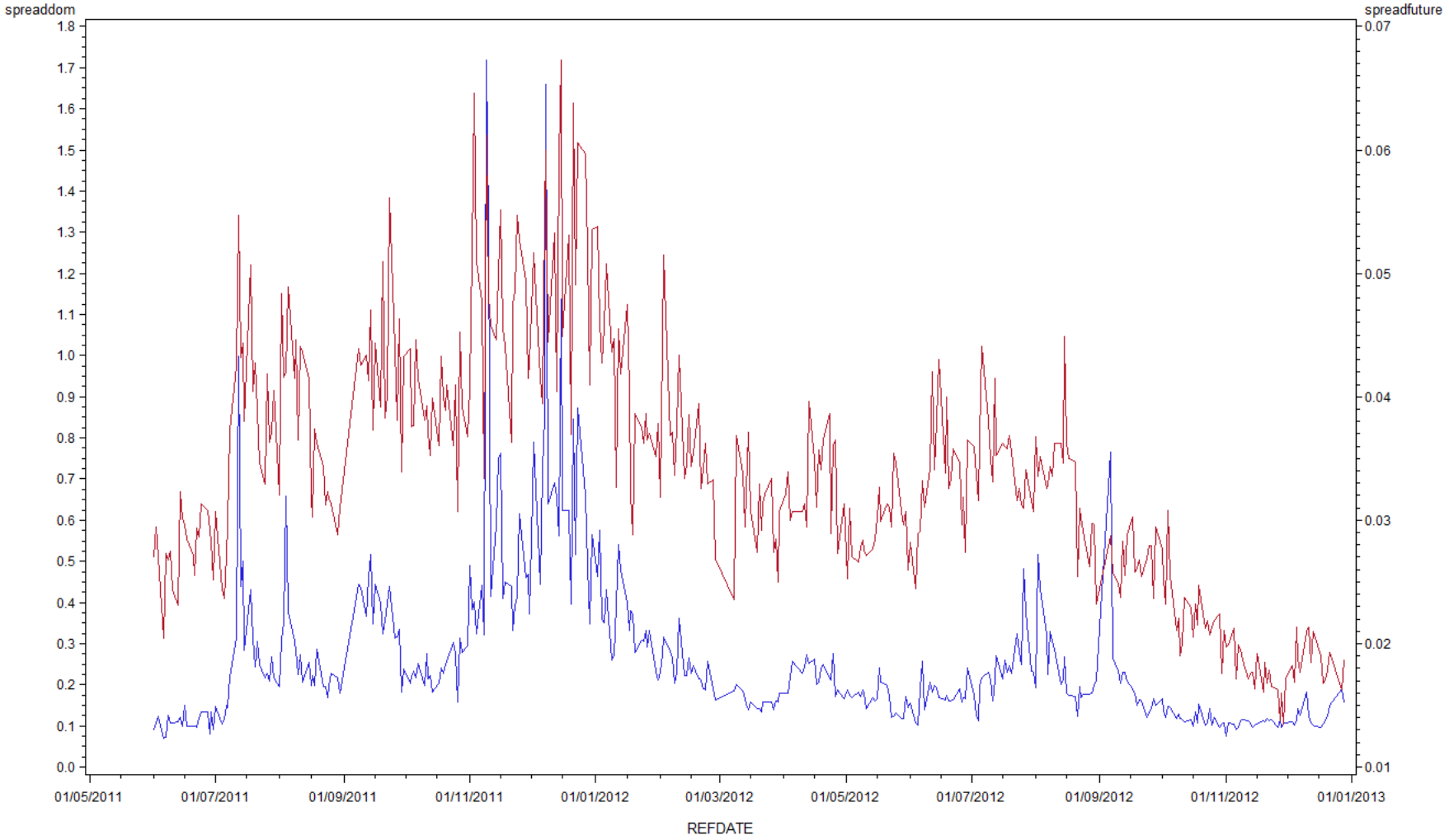


Figure 5: **The Bid-Ask Spreads of the CTD Bond and Futures:** This figure shows the time-series evolution of the bid-ask spread for the CTD bond (left axis, in euros) and corresponding futures price (right axis, in euros).The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

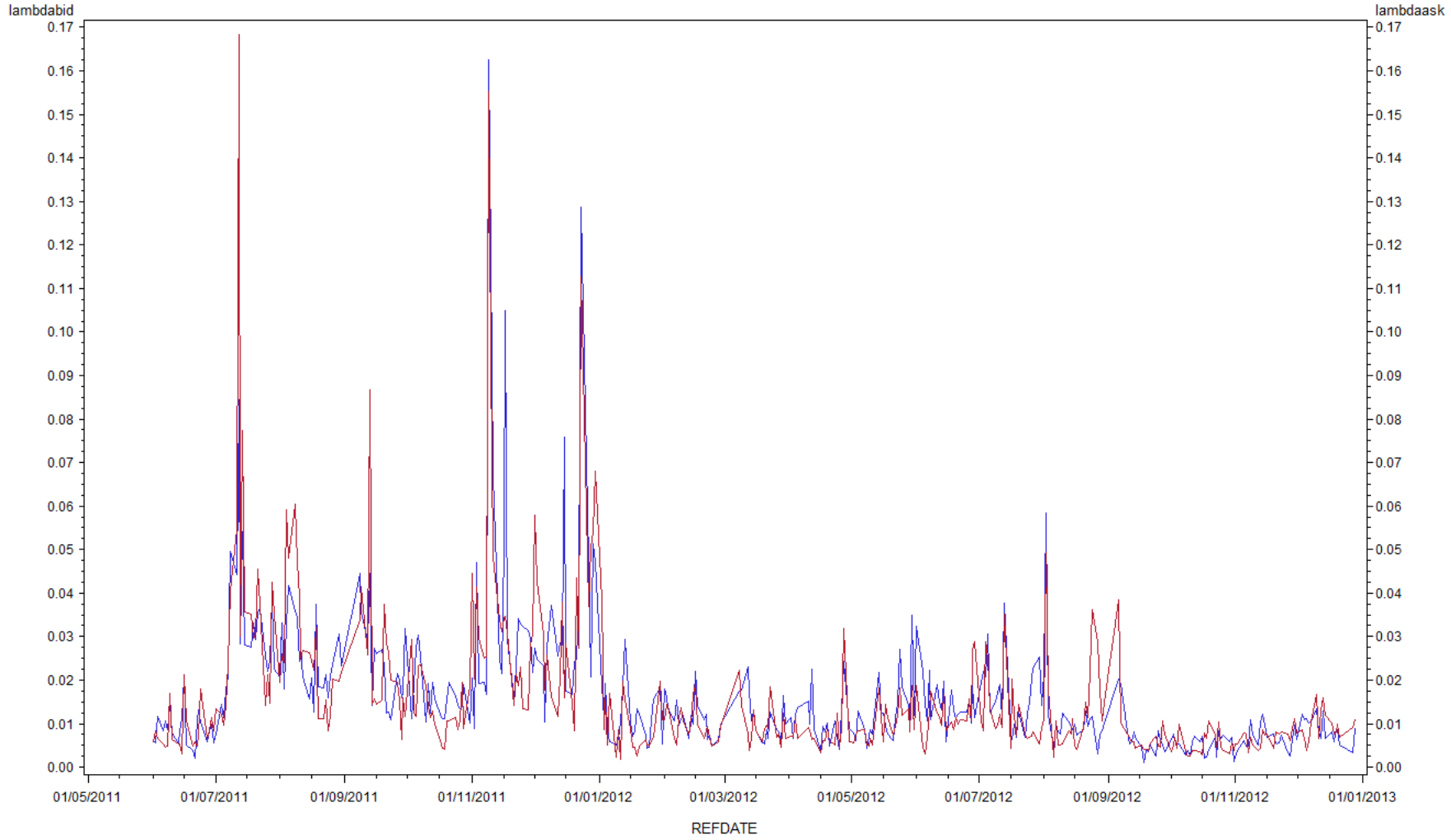


Figure 6: **The λ^A and λ^B Measures:** This figure shows the time-series evolution of the λ measures for the bond market. The measures are defined in Section III. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.

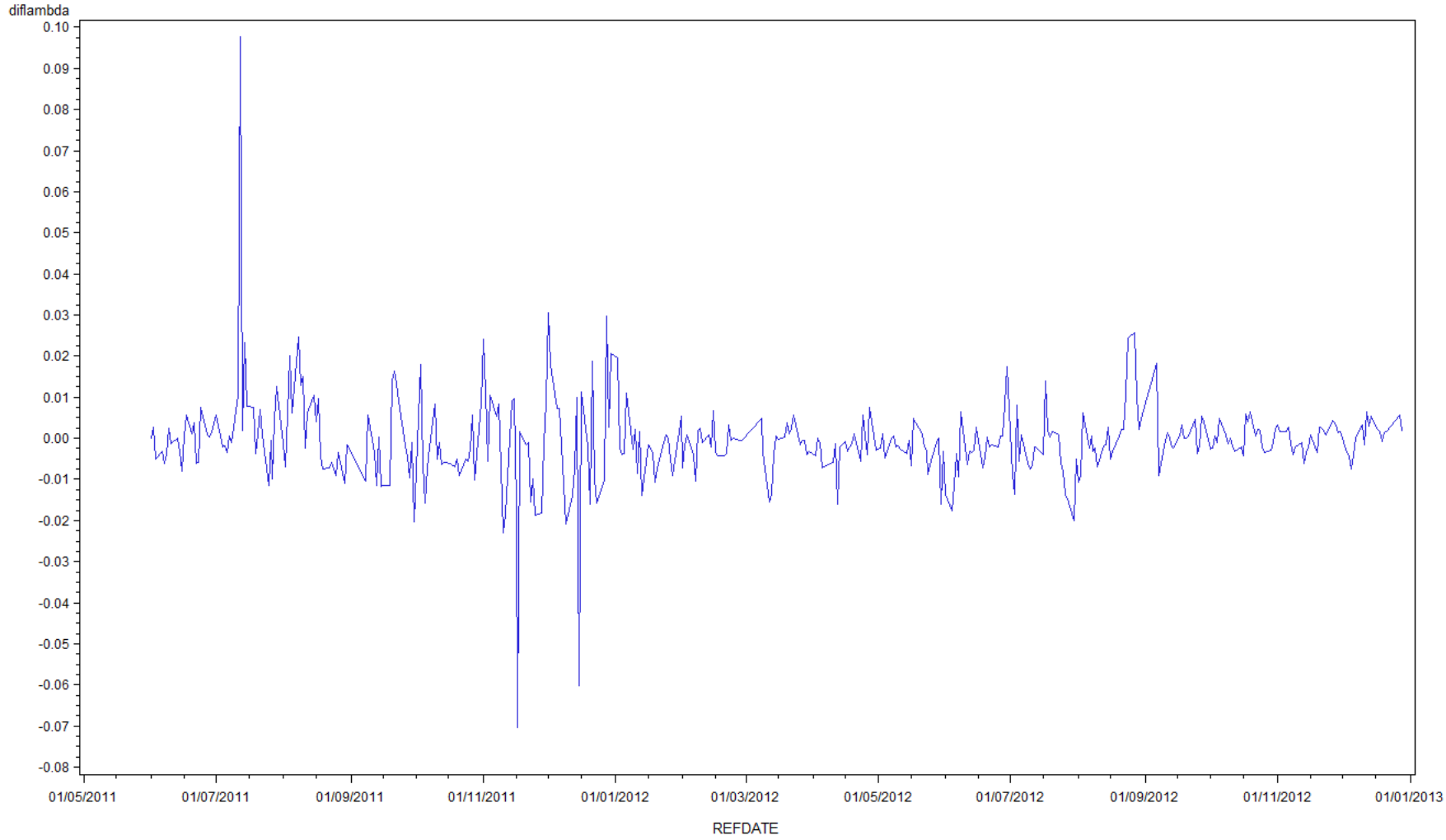
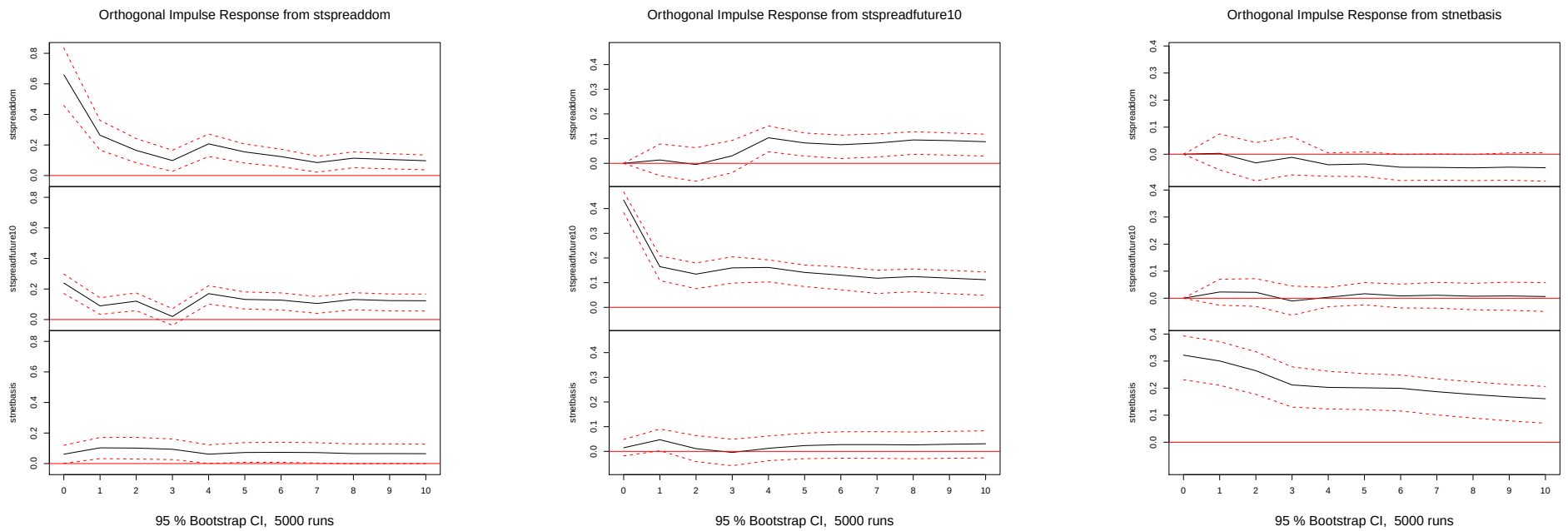


Figure 7: **The $\lambda^A - \lambda^B$ Measure:** This figure shows the time-series evolution of the difference between the λ measures for the bond market. The measures are defined in Section III. The data have a five-minute frequency and are obtained from the MTS and EUREX markets. Our sample period is June 2011 to December 2012.



(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 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.

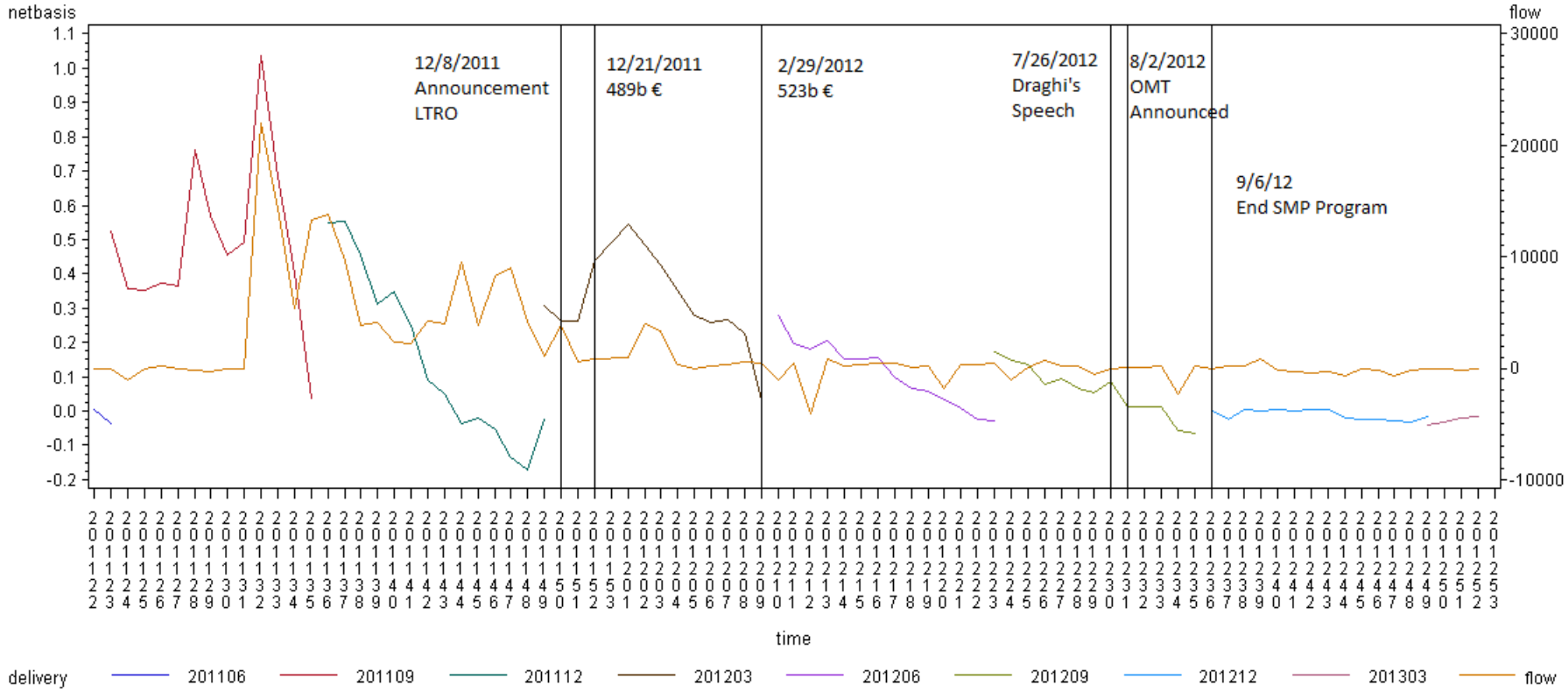


Figure 9: **Basis and ECB Interventions** This figure shows the time-series evolution of the net basis between futures and bond (left axis), and the flow amount of European sovereign bonds that were purchase by the ECB in the context of the SMP intervention. The data are at a weekly frequency. Our sample period is June 2011 to December 2012.

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