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Stefano Corradin; Angela Maddaloni **The importance of being special:
repo markets during the crisis**

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Abstract

We study how the Italian sovereign bond scarcity premia - specialness - in the repo market were affected by the European Central Bank (ECB)'s purchases during the Euro area sovereign debt crisis. We propose and calibrate a search-based dynamic model with a central bank acting as a buy-and-hold investor. Consistent with model predictions, ECB purchases drive specialness of targeted securities in combination with short-selling. Special benchmark bonds entail a positive cash premium but their market liquidity decreases when purchased by the ECB. Short-sellers were more likely to fail-to-deliver very special bonds while holders of these bonds were less inclined to pledge them as collateral to the ECB liquidity operations.

JEL classification: E43, E51, G01, G12, G23.

Keywords: Repo, Specialness, Central bank asset purchases, Short-selling, Market liquidity and Credit risk.

Non-technical summary

On 7 August 2011 the European Central Bank (ECB) re-activated its Securities Markets Program (SMP) in response to the heightened stress in the sovereign bond markets of some euro area countries. Over the following months the ECB bought around 103 billions of Italian sovereign bonds, half of the total volume of bonds bought under the program.

While the purchases were conducted on the bond cash market, their effects transmitted also to other related markets. Repo markets - where a short term loan is guaranteed by the temporary transfer of collateral - are very important and liquid financing markets. They also provide a measure of the premium to be paid for borrowing a scarce security, its specialness. Specialness of Italian government bonds strikingly increased during the period in which the SMP was active, reflecting a very high demand for these bonds in the repo market.

How has the ECB intervention affected the repo markets on Italian sovereigns, in particular their prices and liquidity? We first address this question by using a model of the bond cash and repo markets in which a central bank is a purchaser of assets, typically as a very long-term investor. Guided by the model implications, we investigate how the SMP purchases affected assets scarcity and answer a series of questions on the prices quoted in bond markets, their liquidity and market functioning. We show that when credit risk increases, there is a general increase in short selling positions although bond market liquidity deteriorates. As a result, higher demand for shorted bonds in the repo markets increases specialness. If the central bank decides to purchase the assets in high-demand in the repo markets and does not lend them back, specialness increases further. We find that a purchase corresponding to 1% of the outstanding amount of a security increases its specialness, on average, of 4 basis points at the peak. This effect is also long-lasting, for up to 15 days. Overall the effect of the SMP purchases was also economically significant: it explains around 27% of the observed specialness, but at times it accounted for up to 70%.

How does the increase in specialness affect bond prices and market liquidity? We provide evidence of a scarcity channel looking at ten-year benchmark Italian sovereign bonds. Because the owner of a special bond can borrow at a below-market refinancing rate by using the bond as collateral, the same bond should demand a premium. We show, in fact, that special ten-year benchmark bonds traded at a premium (their price was higher than the price of a comparable bond) in the cash bond markets when purchased through the SMP and short-selling demand was strong. Short-selling activity generally drives both the superior market liquidity of benchmark bonds and their specialness. Instead, we document that specialness and bond market liquidity for these bonds did not move in the same direction. A 1% increase in SMP purchases is associated with more than a two basis point contemporaneous increase in the bid-ask spread of a benchmark bond relative to the bid-ask spread of a comparable

bond.

What are the implications of high levels of specialness for bond delivery? If short sellers borrow a bond in the repo market via a special transaction, they have to deliver exactly the same bond. During the period in which the Eurosystem purchased securities through the SMP, short sellers ended up paying a positive premium to close their positions. They may have decided, therefore, to fail-to-deliver (generally implying the delay of one or more days with respect to the agreed date of delivery of the asset) to limit their losses. Indeed, the probability of a fail-to-deliver increases with the specialness of the bond: a 1 basis point change in specialness increases the probability of a fails-to-deliver by 0.32%.

Overall the analysis in this paper shows how central bank purchases affect specialness and liquidity of purchased bonds, possibly impacting the smooth functioning of bond markets. Restrictions to the available supply of a security can interact with short-selling activity and have sizable and persistent effects on its scarcity premium, its liquidity and use as collateral.

The results provide interesting insights for researchers and policy makers interested in the functioning of very liquid financial markets. The relation between specialness in the repo market and liquidity in the cash market depends on the available supply of a security and needs to be framed in a dynamic model. If there are shocks to the supply, specialness reflects mainly the scarcity of a certain security and its associated illiquidity. Special bonds trade at a cash premium which can persist especially in markets where holders of long positions do not lend the security.

Concerning the implications for policy making, the results clearly underline the importance of the design of central bank asset purchases in order to minimize possible side effects on market functioning. In particular the analysis supports the pivotal role that the central bank can play in the security lending market. When assets are scarce, holders of these securities are unwilling to lend them in the private markets, also for fears that the assets will not be returned timely. Therefore, a policy of promoting security lending by the central bank may be beneficial to support market liquidity and smooth collateral use during these episodes of market stress.

The SMP portfolio was strictly buy-to-hold and purchased securities were not lent out. This is a clear distinction between the SMP and the following programs of central bank purchases in the euro area, in particular the public sector purchase program (PSPP) implemented since March 2015. Indeed the holdings under the PSPP are made available for securities lending in order to support bond and repo market liquidity without unduly curtailing normal repo market activity.

1. Introduction

On 7 August 2011 the European Central Bank (ECB) re-activated its Securities Markets Program (SMP) in response to the heightened stress in the sovereign bond markets of some euro area countries. The stated objective of the program was to *"ensure depth and liquidity in those market segments which are dysfunctional."*¹ Over the following months the ECB bought around 103 billions of Italian sovereign bonds, half of the total volume of bonds bought under the program. Eser and Schwaab (2016), Ghysels, Idier, Manganelli, and Vergote (2016) and Krishnamurthy, Nagel, and Vissing-Jorgensen (2017) focus on the impact of the SMP purchases on sovereign yields.² Instead, our aim is to analyze how the ECB's intervention affected the repo market and impacted further the functioning of the sovereign bond markets.

Repos are used by bond market participants either to finance long bond positions, by borrowing liquidity, or to initiate bond short positions, by borrowing the underlying asset. Therefore, transactions in the cash market are often accomplished by market participants through complementary transactions in the repo market. The repo market is pivotal to ensure market liquidity and funding availability and changes in repo rates and haircuts have important implications for asset pricing (Brunnermeier and Pedersen, 2008 and Gârleanu and Pedersen, 2011) and financial stability (Gorton and Metrick, 2012, Krishnamurthy, Nagel, and Orlov, 2014, Copeland, Martin, and Walker, 2014, Mancini, Ranaldo, and Wrampelmeyer, 2015 and Boissel, Derrien, Ors, and Thesmar, 2017).

In this paper we analyze specialness, the premium of procuring a specific bond in the repo market. This premium results from a special repo rate that is lower than the general repo rate, or general collateral (GC) rate, at which a basket of similar bonds trade (Duffie, 1996). Specialness of Italian government bonds strikingly increased when the SMP was active. Average specialness of Italian sovereigns increased from 12 to 30 basis points but more bonds became more special resulting in a significant increase in the upper tail of the specialness distribution (see Figure 1).³ Specialness of 10-year benchmark bonds reached 400 basis points resulting from negative special repo rates and pointing to a high demand

¹See ECB press release on 10 May 2010 <https://www.ecb.europa.eu/press/pr/date/2010/html/pr100510.en.html>.

²For evidence of the Federal Reserve's impact on yields during the quantitative easing operations see for example Krishnamurthy and Vissing-Jorgensen (2011), Hancock and Passmore (2011), Gagnon, Raskin, Remache, and Sack (2011), D'Amico and King (2013) and Song and Zhu (2018b).

³The figure plots the empirical distribution of specialness for the 50th, 70th and 90th percentile. Specialness is calculated as the difference between the general repo rate and the special repo rate on a specific security and day of trading. The rates refer to repo transactions with underlying Italian sovereign securities as traded on the MTS repo platform from 1 October 2009 to 7 July 2012. See Subsection 3.1 for a detailed description of the variables and the data sources.

for these bonds in the repo market.

[Insert Figure 1 near here]

We investigate the effects of ECB purchases on scarcity of assets in repo markets. We address a series of questions: What is the interrelation between the scarcity of a specific bond in the repo market and credit risk of the same bond during crisis times? How does this interrelation change due to central bank purchases? What are the implications for market liquidity? What are the consequences of high levels of specialness for asset delivery and collateral use? We empirically investigate such interactions relying on an unique dataset of cash and repo transactions obtained from the Mercato dei Titoli di Stato (MTS), one of the largest electronic trading platform for sovereign bonds and the leader for the trading of Italian sovereign bonds. We complement the dataset with data on fails-to-deliver from Monte Titoli, the central securities depository of the MTS platforms. We use this information to assess whether high levels of specialness can be linked to fail-to-deliver transactions.

Our first contribution is to extend the search-based dynamic model by Vayanos and Weill (2008) by introducing the central bank as a key player in crisis times. In Vayanos and Weill (2008) assets with identical cash flows can trade at different prices. Trades involve a cash market for buying and selling assets and a repo market where short-sellers can borrow assets. If short-selling activity is concentrated on a specific asset, this asset trades at a higher price and demands a cash premium. The cash premium arises from positive liquidity and specialness premia. Since the asset has a larger pool of buyers, it is easier to sell and thus carries a liquidity premium. At the same time, because its owners can lend it to short-sellers for a fee, it also carries a specialness premium. In this framework, we introduce a central bank with a distinctive trading behavior consistent with the observed characteristics of the actual implementation of the SMP. First, the central bank is a buy-and-hold investor effectively decreasing asset supply over time because the purchased asset becomes locked away in its portfolio. Second, the central bank does not lend the asset to short-sellers in the repo market. We calibrate the model using parameters derived from actual data from the MTS cash and repo market before (October 2009-July 2011) and during the crisis period (August-December 2011). The calibration using crisis parameters allows to assess the impact on specialness of increased sovereign bond risk premia and market liquidity deterioration as documented by Pelizzon, Subrahmanyam, Tomio, and Uno (2016). A key and distinctive implication of our model with a central bank purchasing assets is that specialness and market liquidity do not move in the same direction. As the asset becomes locked away in the central bank's portfolio, the effective asset's supply decreases, its market liquidity worsens but specialness increases as the asset becomes scarcer in the repo market.

The model provides three novel empirical predictions that we test. First, we validate the empirical prediction that specialness increases with short-selling activity in crisis times. The increase in risk induces higher demand from short-sellers to borrow the asset in the repo market and to hedge their positions. Therefore, specialness rises. We provide empirical evidence of a risk short-selling channel as a driver of the relation between credit risk and specialness. We first investigate such interaction running panel regressions including regressors that can be linked to demand and supply factors in the cash and repo market and controlling for bond market liquidity and Italian sovereign credit risk through credit default swaps (CDS). Because we have information on the trading direction of repo transactions, we compute a *repo imbalance* measure that proxies for the demand in the repo market from short-sellers. We find that the coefficients of lagged repo imbalance and CDS spread are statistically and economically significant in explaining specialness. We also show that these measures have an impact on the distribution of specialness, inducing a fatter right-hand tail. To determine the dynamic relation between short-selling demand, credit risk and specialness, we estimate a panel Vector Autoregression (VAR) with the same set of regressors and assess the impact of the main variables using impulse response functions. We find that an increase in CDS spread leads to an increase in repo imbalance. A positive shock of 1% to the repo imbalance leads to an increase in specialness of 5 basis points. Credit risk does not directly affect specialness.

The second empirical prediction highlights the interaction between short-selling activity and central bank purchases in crisis times. Central bank purchases increase specialness further by activating the scarcity channel in the repo market. Because the central bank does not lend the assets in the repo market, fewer lenders can extract a higher specialness premium from short-sellers. We find that bonds bought by the ECB had higher specialness, consistent with similar regression analysis carried out by D'Amico, Fan, and Kitsul (2018), who analyze the impact of the Federal Reserve (Fed) outright purchases on the special US Treasury repo market, and by Song and Zhu (2018a) who examine how the Fed lending facility affected specialness of mortgage backed securities (MBS) during its quantitative easing operations.⁴ Relying on the VAR framework, we find that a SMP purchase shock of 1% of the outstanding amount of a security increases its specialness, on average, of 4 basis points at the peak, which is reached after around 3 trading days. The impact on specialness is always significant and persistent for up to 15 days, suggesting long-lasting effect. Conversely, we find that a shock to specialness does not have a statistically significant impact on SMP purchases: higher

⁴Song and Zhu (2018a) provide evidence that when the Fed lends mortgage backed securities in certain coupon cohorts via repo transactions (or dollar roll), the specialness in the affected coupon cohorts decreases significantly, in the order of about 50 bps, relative to coupon cohorts in which the Fed does not lend. This evidence suggests that the Fed's dollar roll sales effectively mitigate the supply shortage of agency MBS during its QE operations.

specialness did not result in larger SMP purchases. Therefore, we do not find evidence that the ECB was targeting the bonds with heightened specialness. We also perform a historical counterfactual decomposition and show that the effects of the SMP purchase shocks were also economically significant. On average purchase shocks explain around 27% of the observed specialness, but at times they account for up to 70%.

The third empirical prediction concerns the link between the concentration of short-selling activity and central bank purchases on on-the-run (or newly issued) bonds. As implied by our model, we expect that if specialness is strongly associated with short-selling activity and central bank purchases, bond market liquidity decreases, but the bond, overall, trades at a cash premium. This is an important prediction because in Vayanos and Weill (2008) short-selling activity drives both the superior liquidity of the on-the-run bond and its specialness. Previous empirical literature also confirms such link in normal market conditions (Jordan and Jordan, 1997, Krishnamurthy, 2002, Buraschi and Menini, 2002, Sundaresan and Wang, 2008 and Graveline and McBrady, 2011).⁵ In contrast, our calibration exercise shows that in crisis times and with a central bank acting as a buy-and-hold investor, bond's supply is reduced over time and hence its market liquidity. At the same time, we should still observe a positive cash premium because the scarcity premium in the repo market (specialness) tends to offset the lower liquidity premium.

To test this empirical prediction, we proceed in two steps. First, we compute the cash premium from a trading strategy composed of a long position in the off-the-run bond and a short position on the on-the run bond along the lines of what proposed by Krishnamurthy (2002). We regress the cash premium at the bond level on specialness and SMP purchases. We find a positive and robust relationship between cash premium, specialness and SMP purchases. This is consistent with previous evidence of this phenomenon both in the US Treasury market (see for example Amihud and Mendelson, 1991, Jordan and Jordan, 1997, Krishnamurthy, 2002, Buraschi and Menini, 2002, Goldreich, Hanke, and Nath, 2005, Pasquariello and Vega, 2009, Banerjee and Graveline, 2013 and D'Amico, Fan, and Kitsul, 2018⁶) and in other countries (see for example for Japan Boudoukh and Whitelaw, 1991 and Boudoukh and Whitelaw, 1993). As expected, cash premium and SMP purchases are strongly positively correlated. A 1% increase in SMP purchases is associated with a 2.5 basis points increase in cash premium. To test the implications for market liquidity we estimate similar panel

⁵Jordan and Jordan (1997) provide evidence supporting this view. Buraschi and Menini (2002) examine the term repo spread which is regarded as an indicator of the duration of expected specialness in the repo markets. They show that the violation in the expectation hypothesis may be due to the presence of time-varying liquidity premium in government debt securities. Krishnamurthy (2002) explores the relationship between on/off-the-run spread and the spread between commercial paper and Treasury bill.

⁶D'Amico, Fan, and Kitsul (2018) find that this premium is significantly stronger on the days of the Fed operations and for securities eligible for the Fed purchases.

regressions in which the dependent variable is the bid-ask spread differential between the on-the-run and the off-the-run bonds purchased by the ECB. Empirical evidence supports the model prediction. A 1% increase in SMP purchases is associated with more than 2 basis points increase in the bid-ask spread differential. Together, this evidence suggests that the positive cash premium enjoyed by on-the-run bonds derives from the scarcity premium in the repo market. In the second step of the analysis, we regress the short-selling premium on specialness and SMP purchases. The short-selling premium is computed using the decomposition of the cash premium of Banerjee and Graveline (2013). We find that the cost of short-selling and SMP purchases are strongly positively correlated, in particular around the futures contract delivery dates. Short-sellers paid on average net positive premia, resulting from the long position held by the ECB.

Finally, we investigate the implications of high levels of specialness for asset delivery and collateral use. We analyze fails-to-deliver episodes and funding conditions for bond holders. A key feature of special repo markets is that short-sellers have to deliver the bond they borrowed. Short-sellers may have difficulty delivering the bond they borrowed, when the bond is scarce and very special. Previous literature has investigated these effects mainly in the stock market (Evans, Geczy, Musto, and Reed, 2009 and Fotak, Raman, and Yadav, 2014). Some evidence for the US Treasury market is provided in Fleming and Garbade (2005) and more recently in Fleming, Keane, Martin, and McMorro (2014). They document that traders fail to deliver on highly special US Treasury bonds, even if they incur in penalties. We provide evidence that fails-to-deliver are linked to specialness and SMP purchases. We find that the probability of a fail-to-deliver increases with the specialness of the bond: a 1 basis point change in specialness increases the probability of a fails-to-deliver by 0.32%. Thus, the probability of a transaction to end with a delivery failure increases for bonds that were bought by the ECB.

The owner of a special bond can borrow at a below-market refinancing rate by using the bond as collateral. This premium can be particularly valuable when funding conditions are tight as during a crisis. We provide indirect evidence of this funding channel looking at the collateral pledged by banks for the ECB liquidity operations. We find a negative correlation between specialness and amount pledged at the ECB for very special bonds. This result suggests that banks responded to the increased specialness of some bonds by presumably using them in the private repo to borrow at cheaper rates than the ECB monetary rate or lending them in the security lending markets. Our evidence is consistent with recent empirical literature documenting how market participants actively manage their bonds as collateral (Aggarwal, Bai, and Laeven, 2018 and Jank and Moench, 2019).

The paper is organized as follows. Section 2 provides institutional details on repo markets

and the SMP programme. In Section 3 we describe the data and present our descriptive statistics. In Section 4 we present our model and derive three empirical implications that are tested in Section 5. We present results on fails-to-deliver and collateral utilization in Section 6. Section 7 concludes.

2. The repo market during the euro-area sovereign debt crisis

2.1. Special repo market

A repo transaction combines two financial transactions legs taking place at different times. It involves the sale of a security at the spot price and a forward agreement to buy back the same security at a future specified date and price. Repo rates are implied by the difference between the two prices. The repurchase agreement may entail to buy back the next day (overnight repo) or at a later date, usually up to one year. However, the most common maturity for repos on electronic platforms is one-day.⁷ The party lending the security in the first transaction in exchange of liquidity (possibly to finance the original purchase of the bond) is entering a (financing) *repo* agreement, while the party that borrows the security and commits to deliver it at the agreed future date enters a *reverse repo*.⁸

There are two types of repo transactions: *special repos* and *general collateral repos*. In special repos, the party delivering the security must deliver a specific asset (with a specific ISIN code), while in general collateral repos (GC repos) he/she can choose among a basket of possible assets. Special repos imply the payment of a special rate. The special rate can be lower than the general repo rate, reflecting the convenience yield of the asset - how much sought-after the asset is. Special rates can even become negative, in cases of extreme market squeezes, when the counter party lending liquidity is willing to pay a premium (and therefore forgo the return on the loan) in order to get a security on special.

We base our analysis on data on special repos traded on the MTS Repo electronic platform with Italian sovereign securities as collateral. The MTS Repo platform covers a significant percentage of the European market transactions and a leading share of the Italian repo

⁷There are three types of transactions: *overnight*, when the repo settles on the trade date T and the bond is repurchased the next business day $T + 1$; *tomorrow next*, when the repo settles at the trade date plus one business day $T + 1$ and the bond is repurchased the following business day $T + 2$; *spot next* when the repo settles at $T + 2$ and the bond is repurchased at $T + 3$.

⁸Since a repo transaction is composed by the two legs happening in sequence, the two parties are effectively borrowing and lending liquidity. Legally, however, all transactions may be treated as "true sales", which is the case for example for transactions taking place on the electronic trading platform MTS repo.

market. Miglietta, Picillo, and Pietrunti (2015) document that a large majority, up to 90%, of the current repo transactions on the MTS Repo platform is CCP-cleared. There are two CCPs involved in the clearing of the Italian repo market: LCH Clearnet SA and Cassa Compensazione and Garanzia (CC&G). In centrally cleared repo transactions, CCPs require both parties to post initial margins on the net of amount collateral due. The aim is to provide the CCPs with sufficient resources to mitigate potential financial risks.⁹

Recent studies on the European repo market have also focused on the tensions occurring during the Great financial crisis and the Euro area sovereign debt crisis. Mancini, Ranaldo, and Wrampelmeyer (2015) analyze how Euro area repo market activity responded to financial stress from 2006 to 2013 using a dataset on GC repo transactions from the Eurex Repo platform. Their main finding is that repo activity via CCP was resilient during crisis episodes. They identify two main characteristics that made the market resilient: anonymous trading via CCP and reliance on safe collateral. In contrast, using data from the BrokerTec and MTS platform, Boissel, Derrien, Ors, and Thesmar (2017) find that repo market became highly stressed at the peak of the crisis in 2011. Their analysis documents that repo rates responded to movements in sovereign risk suggesting that CCP-intermediated repo market was vulnerable to sovereign risk itself.¹⁰ We also restrict the analysis mainly to crisis periods; however, we are interested in extracting the effect of shocks to security-specific supply and demand on repo rates, and we restrict the analysis only to one sovereign (Italy).

2.2. *Security Market Programme*

During this period the ECB bought and subsequently held large amounts of Italian sovereign bonds, through the implementation of the Security Market Programme (SMP). The purchase programme had some distinctive features that we expect to have an impact on specialness. The ECB did not disclose the total amounts which would be spent for the purchases, the time frame over which the program would be active, or the set of securities that would be targeted. Therefore, markets participants had limited ability, especially over the short time, to readjust their portfolios in response to the purchases. In addition, the SMP portfolio was strictly buy-to-hold and purchased securities were not lent out reducing *de facto* the available supply of the bonds in repo market. This is a distinctive feature of the

⁹In addition, both parties may be asked daily to post variation margins following mark-to-market valuation of individual positions vis-a-vis the CCP.

¹⁰One possible explanation is that Eurex Repo data consists of GC pooling collateral transactions. The crucial difference is that GC Pooling lumps together all sovereigns graded above a3/A-, while GC repos are not pooled in BrokerTec and MTS Repo platform and each country has a separate repo market segment. Therefore, there are potentially stronger linkages between government debt and the repo rate in the latter ones.

SMP compared to the programs of outright purchases implemented by the Federal Reserve in 2009 – 2012 and the public sector purchase program (PSPP) by the ECB since March 2015.

3. Data and summary evidence

3.1. Description

In the following sections we describe in detail the data that we use in the analysis and how we have integrated different sources to compile an exhaustive database.

The main dataset used in our analysis is a sample of the transactions recorded in the MTS Repo trading platform. We have tick-by-tick transaction-level information from 1 October 2009 to 7 July 2012, including the type of repo contract (GC or special), the ISIN of the underlying government bond, the repo interest rate paid on each transaction, the volume of the transaction, the spot and the end price of the underlying government bond, the maturity of the repo and the direction of the trading (reverse vs financing).¹¹

We define the variable specialness as the difference between the general repo rate and the special repo rate on a specific security, repo maturity and day of trading

$$\text{Specialness}_{i,j,t} = \text{GCrate}_{j,t} - \text{Special rate}_{i,j,t}. \quad (1)$$

We calculate specialness of security i using all security-level transactions in the repo market on day t . Specifically, we take the first available GC rate for each repo maturity j (where j is overnight, spot next or tomorrow next) that we observe. Every time we observe a new transaction for each maturity j , we update the GC rate. Specialness is the difference between the most recent GC rate with repo maturity j and the special rate of a security i with the same repo maturity. To construct daily observations, we average this difference during day t for each bond i and repo maturity j . The average is weighted by the nominal amount of each special repo transaction. We select only transactions with one-day maturity (overnight, tomorrow next and spot next). In the empirical analysis we further restrict the sample to tomorrow next and spot next transactions since we want to explore the links between the cash and the repo market. In particular, we focus on repo transactions where it is more likely that one of the counterparty needs to hedge against a position previously acquired in the cash market. Settlement is two-day in the cash market trading on MTS, therefore the

¹¹See Adrian, Begalle, Copeland, and Martin (2013) for the important information needed to analyze the repo market. Differently from what happens in bilateral repos, there are no haircuts applied on the MTS electronic platform by the two trading parties.

most relevant repo maturity are spot next and tomorrow next. These transactions account for almost 98% of the total observed in our sample (see Table 1 of the Online Appendix).

We also define a measure of security-specific demand in the repo market. Because we have information on the trading direction of the repo, we define the variable repo imbalance for security i and repo maturity j at time t as

$$\text{Repo imbalance}_{i,j,t} = \frac{\text{Reverse repo}_{i,j,t}}{\text{Outstanding amount}_{i,t}} - \frac{\text{Financing repo}_{i,j,t}}{\text{Outstanding amount}_{i,t}}, \quad (2)$$

where reverse (financing) repo is the aggregate reverse (financing) special repo transactions at security-repo maturity level on a daily basis. Outstanding amount is the total volume of the security i that has been issued until date t . A positive value of the repo imbalance suggests the presence of market pressures from traders looking to borrow a security and lend liquidity. Repo imbalance tends to be persistent, suggesting that special bonds are demanded in the repo market over consecutive days (the autocorrelation is around 24%).

We include information on the primary issuance of Italian sovereign bonds in the dataset. The daily amount outstanding of each bond (at the ISIN level) is reported using detailed issuance data from the Italian Treasury and the Bank of Italy. Given the large outstanding amount of the Italian government debt, bonds are issued by the Italian Treasury in (relatively small) tranches that however preserve the same maturity date and ISIN code. Normally, a new bond (with a new ISIN code) is issued in sequential tranches of about the same volume.¹² The currently issued bond is considered the *on-the-run* security for a certain maturity until a new bond (ISIN) with the same characteristics is issued. From time to time, to increase the liquidity of a specific security, the Italian Treasury may decide to reissue a tranche of an *old* bond - a bond that is currently off-the-run.¹³ The issuance of a security in the primary market may have an impact on the prices observed in the repo market. Therefore, in our estimation we include a time dummy in correspondence of a new issuance.

The outstanding amount of a security is a proxy for the total supply of that security. However, the amount of security that is actually *available for trading* is typically much lower, especially for securities that have been issued since long time. A sensible measure of the available supply of a security is the amount of that security that is available for lending. Institutional investors and other buy-and-hold financial intermediaries are typically willing to lend securities held in their portfolio to other market participants. The borrowers may use

¹²An average number is for example six consecutive tranches for BOTs, the securities with maturity up to one year. However, there are no fixed rules on the number of tranches that will be issued and/or on the amount issued each time, which preserves some flexibility for the Italian sovereign debt management office.

¹³Beetsma, Giuliodori, De Jong, and Widiyanto (2016) provide a comprehensive analysis of the Italian sovereign primary issuance market.

the securities to cover short positions and/or manage their financial portfolio. These data are available from Data Explorers. We use the quantity of a certain security that is available for lending divided by the outstanding amount as a proxy for the available supply of that security. Available for lending also proxies for the collateral re-use of a certain security.

We also define a measure of imbalance in the cash market. We define the variable cash imbalance as the difference between the sell initiated volume and the buy initiated volume of a single security on the MTS cash market. We have this information at a daily frequency from the MTS bond trading platform.¹⁴ For each security i , we define

$$\text{Cash imbalance}_{i,t} = \frac{\text{Sell volume}_{i,t}}{\text{Outstanding amount}_{i,t}} - \frac{\text{Buy volume}_{i,t}}{\text{Outstanding amount}_{i,t}}. \quad (3)$$

This measure reflects the *direction* of the cash market and the possible pressures stemming from short-selling. A positive value would suggest that the market is *short* on security i .

In the analysis we also use traditional measures of market liquidity computed at bond level as control variables. We consider the time-to-maturity of the bond as a proxy for the liquidity of that bond stemming from its age. Usually bonds that have been issued earlier tend to have lower liquidity, partly because it is likely that significant holdings of these bonds are in the hands of buy-and-hold investors and are therefore not readily available for trading in the market. Note that this concept is related, but not coincident with an issue being on/off-the-run. We include the daily bid-ask spread, which controls for the liquidity pressures stemming from the cash market. Bid-ask spread refers to BGN Bloomberg prices at or before 5pm. Another measure of bond market liquidity is the cash turnover ratio that we use to calibrate the model. This measure is computed as the total volume traded in the cash market over the nominal amount outstanding of the bond.

The Italian sovereign risk is measured by the term structure of US dollar-denominated Italian sovereign CDS contracts obtained from Bloomberg. On every day we interpolate the term structure of CDS spreads and match the implied CDS spread with each bond in our sample using the time-to-maturity of the bond itself. An alternative potential proxy for Italian sovereign risk is the margins applied on repo transactions by central counterparty clearing houses (CCPs). We collect data from Cassa Compensazione and Garanzia (CC&G), the main CCP for the MTS platform. As a robustness check, we will also report our main empirical results using the CCP margins instead of CDS spreads at bond level.

To assess the impact of the SMP on specialness, we include data on the SMP bond

¹⁴MTS has two trading platforms where it is possible to trade Italian government bonds, an Italian and a European platform. Volumes are much larger on the domestic platform, but for completeness we have gathered data from both sources.

purchases. $SMP\ purchase_{i,t}$ is the nominal amount bought by the ECB of security i on day t over the nominal outstanding amount of that security.

To test one of our empirical predictions we analyze the Italian 10-year (or long term) sovereign futures contracts. Futures data are obtained from Eurex, a major stock and futures exchange, and encompass information on the deliverable bonds for every delivery date identifying the cheapest-to-deliver bond and the implied net basis of each bond.

Finally, to investigate how fails-to-deliver are linked to specialness, we gathered data on fails-to-deliver involving transactions on Italian sovereign bonds from Monte Titoli, the main central securities depository for the Italian sovereign bonds. Data are reported at security level on a daily basis, but no distinction is available for fails taking place on different markets (for example for fails on the repo vis-a-vis the cash market). Settlement fails are reported on a cumulative basis, which implies that the volume of fails is equal to the number of days for which a transaction has not been settled times the volume of the failed transaction. Our measure of fails-to-deliver at security level is calculated as the nominal amount of fails over the total nominal amount of that security settled by Monte Titoli.

3.2. *Summary evidence*

Our dataset includes data on the MTS repo transactions on Italian government bonds from 1 October 2009 to 7 July 2012. During the summer of 2011, specialness increased significantly both in average and dispersion. More bonds became more special resulting in a significant increase in the upper tail of the specialness distribution (Figure 1).

Starting from this observation, we divide the entire sample in three distinct sub-periods: the *pre-crisis*, *crisis* and *post-crisis* period. The first sub-period runs from 1 October 2009 to 7 August 2011, the date when the ECB decided to reactivate the SMP and started open market purchases of Italian sovereign bonds. During the summer and fall of 2011, yields of Italian sovereign bonds increased and remained very volatile. As result, Italian sovereign CDS went up and CCPs raised margins on Italian sovereign bonds, because the sharp rise in yields had reduced their collateral value (Figure A-II in the Appendix). We end the *crisis* period on 21 December 2011, the day before the ECB conducted the first 3-year Long Term Refinancing Operation (LTRO).¹⁵ The *post-crisis* period extends from 22 December 2011 to

¹⁵The ECB engages in two types of market operations: main refinancing operations (MRO) and longer-term refinancing operations (LTRO). MROs are regular liquidity-providing transactions with a weekly frequency and a maturity of one week. LTROs are liquidity-providing transactions offered every other week and usually have a maturity of one to three months. On two occasions during the time period that we consider, the ECB decided to provide liquidity with longer maturities, a 1-year LTRO (July 2009) and a 3-year LTRO (December 2011 and February 2012). After October 2008, the ECB has allocated liquidity by conducting fixed-rate auctions with full allotment.

12 July 2012 and it includes the second 3–year LTRO, conducted on 1 March 2012.

During the crisis period specialness increased on average for all bonds and its distribution became more skewed with a fatter tail. Table 1 reports in the first row descriptive statistics for specialness for the overall period and the three sub-periods considered. During periods of market stress (from 8 August to 21 December 2011), average specialness of Italian government bonds increased significantly: the average was almost three times compared to the previous period. Standard deviation also increased. Most notably, mean and standard deviation of specialness were higher for bonds purchased by the ECB (see figures in parenthesis). During the last period, specialness reverted back to the historical average and the standard deviation declined dramatically. A plausible explanation is the implementation of the first 3-year LTRO on 21 December 2011, which provided 489.2 euros billion to 523 credit institutions. Pelizzon, Subrahmanyam, Tomio, and Uno (2016) document that, following the ECB intervention, the improved liquidity in the Italian government bond market strongly attenuated the dynamic relationship between credit risk and market liquidity.¹⁶ At the same time, the ECB stopped buying euro area sovereign bonds in mid-January 2012.¹⁷

Table 1 reports descriptive statistics for all other explanatory variables. Looking at demand measures, it is noticeable that repo imbalance, the security-specific demand in the repo market, calculated for all the bonds traded on MTS Repo platform, substantially decreased in the crisis period becoming negative. Indeed, during this time, more traders were willing to borrow liquidity offering as collateral specific securities to take advantage of very low special rates. We observe that indeed during the crisis period there was a significant increase in the volume of special transactions vis-a-vis GC transactions (Figure A-III in the Appendix).¹⁸ However, when the statistics are computed only on the set of securities purchased by the ECB, repo imbalance is positive, suggesting that these securities were instead in high demand in the repo market. At the same time, selling pressures in the cash market increased dramatically for the bonds in our sample, and much more for bonds that were purchased by the ECB, looking at the statistics related to cash imbalance.

¹⁶Table A-I in the Appendix shows the distribution of specialness by buckets. In the first part of the sample, most of the observations, around 90%, were concentrated in the first bucket, with specialness ranging between 0 and 25 basis points. Between August and December 2011, only 56% of the observations remained in that class, while about 30% of the securities had a specialness between 25 and 50 basis points. In the same period the frequencies of all the classes with very high specialness increased, with 3% of the bonds recording a specialness of more than 100 basis points. In the Online Appendix we also provide the main statistics for the GC and Special repo rates for the three sub-periods and show that special repo rates were negative in the tails of the distribution during crisis times.

¹⁷Almost no purchases relevant for our analysis, i.e. involving Italian sovereign bonds, were carried out after 21 December 2011.

¹⁸One possible explanation is that parties looking for funds could get better rates in special operations, while, on the other hand, liquidity providers were very reluctant to accept any security in a period of high market stress.

[Insert Table 1 near here]

Turning to supply measures, the amount of securities available for lending declined already during the crisis, which may reflect worries from market participants that the securities would not be returned timely after lending, especially in periods of market stress. Available supply further declined in the post-crisis period, possibly linked to the effect of 3-year LTROs requiring more collateral posting (Aggarwal, Bai, and Laeven, 2018).

We also consider three traditional liquidity measures. The average age of the bond used in repos - bond time-to-maturity - declines especially in the last period, consistent with the substantial decrease in the credit risk priced for the shorter maturities. Instead the average bid-ask spread increased over time pointing to some illiquidity in the cash market for sovereign bonds. However, average bid-ask spread is significantly lower for the set of purchased securities, suggesting that the purchases were directed to generally more liquid assets. The cash turnover ratio points in the same direction of bid-ask spreads showing a lower velocity of the Italian sovereign bonds during the crisis period.

Finally, turning to fails-to-deliver measure, the volume of fails over the exchanged amount does not vary dramatically across the three sub-periods, but it is about 20% higher than in the first period for the bonds purchased under the SMP.

4. Model and testable implications

4.1. Model and calibration

In this section we review and extend the model by Vayanos and Weill (2008) to guide and motivate our empirical analysis.¹⁹ For easiness of exposure we describe here only the key features of the extension that we propose and their implications. A complete derivation of the model is provided in the Section A of the Appendix.

We borrow the framework of Vayanos and Weill (2008) using the same notation. They model an infinite-horizon steady-state economy in which two assets can trade at different prices, p_1 and p_2 , although they pay an identical dividend flow δ and are identical in supply S . There are three types of agents respectively with high, average and low valuation that depends on the correlation between the agent's endowment and the cash flows from the asset. All agents are risk averse and y represents a cost of risk bearing. A high-valuation agent is long one share (of either asset) and derives an extra utility flow \bar{x} from holding that

¹⁹We thank the referee for suggesting we formalize our empirical predictions in a model.

position.²⁰ The average-valuation agent has no position. Instead, the low-valuation agent derives an extra utility flow \underline{x} from shorting the asset 1.²¹ This asset can be viewed as the on-the-run asset. Because short-sellers concentrate in on-the-run asset, the asset endogenously enjoys greater liquidity, a higher lending fee ω_1 (or specialness), and trades at a cash premium consistent with no-arbitrage.

Trades take place in a cash market for buying and selling assets and in a repo market where short-sellers can borrow the on-the-run asset from high-valuation agents who become lenders. Both spot and repo markets operate through search mechanism where agents are matched randomly in pairs over time.²²

Agents experience transitory needs to hold long (or short) positions representing agents' life cycles. Consider the transitions for a high-valuation agent. Once a high-valuation agent buys the asset, he/she holds it until his/her preference for the ownership changes and he/she prefers to liquidate the investment and exits the market. Specifically, at each point in time, there is a flow \bar{F} of average-valuation agents who switch to high valuation. A high-valuation agent seeks a seller of either asset in the spot market. With some probability, modeled as a constant Poisson switching intensity $\bar{\kappa}$, this agent exits the market, if a seller is not found, and reverts to average valuation.²³ Otherwise, the high-valuation agent can meet a seller and buys the asset i with Poisson intensity $\lambda\mu_{si}$, where λ is a parameter measuring the efficiency of the spot market and μ_{si} is the mass of sellers of asset i in the spot market.²⁴ Then, if the same agent buys the on-the-run asset, he/she can become a lender in the repo market. He/she seeks a borrower and lends the asset with Poisson intensity $\nu\mu_{bo}$, where ν is a parameter measuring the efficiency of the repo market and μ_{bo} is the mass of borrowers of the on-the-run asset in the repo market. If he/she reverts to average valuation before meeting a borrower, he/she exits the repo market and becomes a seller of the asset. After becoming a lender, he/she can still sell the asset and reverts to average valuation. We provide all the transitions in the Section A of the Appendix.

We extend the model by Vayanos and Weill (2008) introducing the central bank as a key player. We now have two different high-valuation agents. One is the high-valuation agent as in Vayanos and Weill (2008). The other agent is the central bank who has a different trading

²⁰Vayanos and Weill (2008) model an agent type as many agents type holding (shorting) one asset, rather than an agent type holding (shorting) many assets.

²¹The agents have CARA preferences over a single consumption good. The parameters y , \bar{x} and \underline{x} are function the agents' risk aversion, the variance of the dividend flow, and the endowment correlation.

²²For search and matching in models of dynamic asset market equilibrium see Duffie, Gârleanu, and Pedersen (2002), Duffie, Gârleanu, and Pedersen (2005), Duffie, Gârleanu, and Pedersen (2007), Duffie (2011), Lagos and Rocheteau (2007), Lagos and Rocheteau (2009) and Afonso (2011).

²³The inverse of this parameter provides the expected investment horizon of the agent.

²⁴Meetings between buyers and sellers of asset i occur at deterministic rate $\lambda\mu_{si}\mu_{bi}$ where μ_{bi} is the mass of buyers.

behavior consistent with the distinctive features of the SMP implementation discussed in Subsection 2.2. First, the central bank is a buy-and-hold investor whose propensity to become a seller after buying the asset is lower than the other high-valuation agent, $\bar{\kappa}^{cb} < \bar{\kappa}$.²⁵ In this way, central bank purchases effectively decrease the supply of the asset over time because the asset is locked away in its portfolio. Second, the central bank does not lend the on-the-run asset to short-sellers in the repo market. The main purpose of our model is to characterize how central bank's large holdings of the on-the-run asset are reflected in its specialness, market liquidity and cash premium.

Effectively, we model the central bank as a large, deep-pocket and buy-and-hold investor abstracting from peculiar features of the central bank's role in a sovereign crisis. The participation of the central bank in the market is exogenous. As a result, the central bank does not respond, for example, to an increase in sovereign risk premia buying larger amounts of assets. The modeling of a comprehensive central bank investment strategy in a crisis would require an additional state variable (or stochastic shocks). At the same time, central bank purchases can imply a signal to market participants affecting future outcomes.²⁶ In particular, asset purchases are carried out because the central bank assesses current sovereign yields higher than the values justified based on country fundamentals. This may be due to high liquidity risk and contagion concerns, as it was the case during the euro area sovereign debt crisis. Thus, outright purchases could reduce high uncertainty about future bond yields preventing institutional investors and market makers to retreat from the market, particularly if value-at-risk constraints are binding (see for example Vayanos and Vila, 2009 and Adrian and Shin, 2010, and Pelizzon, Subrahmanyam, Tomio, and Uno, 2016 for anecdotal evidence based on Italian sovereign debt market during the crisis period (August-December 2011)).²⁷

²⁵Because we model an infinite-horizon economy, we still need to account for a positive probability for the central bank to switch to an average-valuation agent and to sell the asset.

²⁶This channel is different from the "signaling channel" discussed in the quantitative easing literature where asset purchases signal future low short-term interest rates (see for example Krishnamurthy and Vissing-Jorgensen, 2011 and Bauer and Rudebusch, 2014). See also the speech by the ECB board member González-Parámo on 4 November 2011 where he states that *'The main purpose of this programme [SMP] is to protect the functioning of the monetary policy transmission mechanism by addressing the malfunctioning of certain key government and private bond market segments. A key distinguishing feature of asset purchases made under the SMP is that their liquidity impact has been sterilised through the conduct of weekly liquidity absorbing operations. There has been no net injection of central bank liquidity to the market as a consequence of these operations. The SMP and its objectives therefore remain fundamentally different from quantitative easing'* (see https://www.ecb.europa.eu/press/key/date/2011/html/sp111104_1.en.html).

²⁷A similar mechanism can have implications for the repo market as well. Duffie, Gârleanu, and Pedersen (2002) present a model of asset valuation in which short-selling is achieved by searching for security lenders and by bargaining over the terms of the lending fee (or specialness). The lending fee increases in the degree of heterogeneity of beliefs of investors about the likely future value of the security. If central bank purchases are effective in reducing high uncertainty about likely future value of the security in a crisis, this would affect the valuation of the short-sellers, reducing short-selling activity and leading to a decline in specialness.

Eser and Schwaab (2016) document that bond yield volatility as well as the probability of observing extreme yield changes were lower for most SMP countries on days in which the ECB purchased bonds.

Also, purchases may be understood as a signal that the central bank is willing to consider and implement non-conventional approaches as a backstop to a sovereign crisis. In a setting of multiple equilibria, a central bank can help coordinate market expectations ruling out a self-fulfilling sovereign crisis as in Corsetti and Dedola (2016). In either case, market participants can learn from the central bank's actions. These extensions are out of the scope of this paper. However, we partly address these limitations using a different parametrization for the crisis and non-crisis times and we will discuss later how our empirical estimates should be affected by these channels.

When we calibrate the model, we use our MTS cash and repo dataset to provide an accurate description of the Italian sovereign bond market before (October 2009-July 2011) and during the crisis period (August-December 2011). The central bank is only active in the latter period to proxy that central purchases is a response to increase in asset risk premia only in crisis times. Table 2 lists the parameters we use for the calibration. We follow the approach by Vayanos and Weill (2008) to calibrate the model.

[Insert Table 2 near here]

We set the number of assets N to 50 consistent with the fact that 10-year on-the-run Italian sovereign bonds account for almost 2% (= 1/50) of the overall outstanding amount of Italian sovereign debt. The expected investment horizon of the high-valuation agents is matched with the cash market turnover of off-the-run bonds.²⁸ The average daily turnover observed is 0.314% (0.466%) during the crisis (non-crisis) period (Table 1). Thus, we set the expected investment horizon at $1/\bar{\kappa} = 1.33$ years (or $333 = 1/0.00314$ trading days) for the crisis period. In non-crisis period off-the-run bonds turn over in less time $1/\bar{\kappa} = 0.85$ years (or $214 = 1/0.00466$ trading days). The turnover of the on-the-run asset is generated by short-sellers. In non-crisis period on-the-run bonds turn over in less time $1/\underline{\kappa} = 0.09$ years (or 22.5 days), while we have $1/\underline{\kappa} = 0.1$ years (or 25 days) for the crisis period.²⁹ These parameters allow us to account for the impact of market liquidity deterioration on search times, specialness and cash premium. For the central bank, as high-valuation agent, we set the parameter at $1/\bar{\kappa}^{cb} = 10$ years for the crisis period to model the buy-and-hold behavior.

²⁸Turnover ratios are calculated as the average daily trading volume in the cash market relative to total outstanding amounts.

²⁹These parameters are based on the turnover of 10-year on-the-run bonds observed on the MTS cash data.

The short-sellers generate the asset supply \underline{F}/κ . This supply over the asset size S is set to approximately match the ratio between 10-year futures volume and the 10-year on-the-run outstanding amount. Trading activity in the futures market is far greater than that in the cash bond market and increased during the crisis period. Total volumes in euros were 107 and 1,288 million, respectively, for the 10-year on-the-run bond and the futures contract for Italian sovereigns. The ratio between 10-year futures volume and the 10-year on-the-run outstanding amount is on average 5% in the non-crisis period, but it increased to 12% in the crisis period reaching 55% around the futures delivery in September 2011. Hence, we let $\underline{F} = 0.1$ (0.01) for the crisis (non-crisis) period. The flow of high-valuation agents entering the market, \bar{F} , is set so that the demand of high-valuation agents exceeds asset supply, including the amount short sold by low-valuation agents. The flow of the central bank, \bar{F}^{cb} , is chosen to approximately match the ECB holdings of the on-the-run and off-the-run assets.

The risk free rate r is set at 1.41% (1.11%) for the crisis (non-crisis) period as the average ECB rate on the main refinancing operations. We select the hedging benefit parameter for the high-valuation agent \bar{x} and the cost of risk bearing y in order to match the Italian 10-year sovereign bond risk premia measured as the difference between bond yields and the ECB refinancing rate.³⁰ Since assets' risk premia are about 3.27% during the non-crisis period, we let $y = 0.73$. Due to the increase in Italian sovereign credit risk, assets' risk premia reached 6.29% during the crisis period. Thus, we let $y = 0.79$ during this period, implying an increase in cost of risk bearing. We set \bar{x} at 0.15 for the non-crisis and crisis period.³¹ As in Vayanos and Weill (2008), the model implies several restrictions on the hedging benefit parameter for the low-valuation agent \underline{x} .³² We take the largest possible value in order to generate empirically plausible effects on specialness and cash premium. Thus, we set \underline{x} at 2.95 (2.63) for the crisis (non-crisis) period. Finally, we set the dividend rate δ at 1.³³

We set the parameter λ for the cash market contact intensity at 10^6 as in Vayanos and Weill (2008). We select a lower value for the parameter ν for the repo market contact intensity, 5×10^4 . These parameters measure the time it takes investors to find a counterparty but they are difficult to measure. We check that the search times implied by the model are short, in the order of hours for on-the-run assets and of days for the off-the-run assets, considering that both cash and repo MTS transactions are executed on a trading platform.

³⁰In the model, the assets' risk premia are measured by the difference between the asset expected return and the risk-less rate, $\delta/p_i - r$.

³¹Matching the risk premium of the Italian 10-year sovereign bonds is only one condition, while there are two parameters (\bar{x}, y) . The second degree of freedom in these parameters appears to have a small effect on the calibration results.

³²The following parameter restrictions are imposed: i) $\bar{x} + \underline{x} > 2y > \bar{x}$; and ii) $4y > \bar{x} + \underline{x}$. See Section V of Vayanos and Weill (2008).

³³The dividend rate does not affect prices and specialness. We set at 1 because we report relative prices.

Moreover, the search times might seem long but should be interpreted as an average across asset owners, some of whom do not engage in asset trading and lending in practice. Finally, we assume that the buyer and lender bargaining powers, ϕ and θ respectively, are equal implying that all agents are symmetric. This is a standard assumption of the search based model literature.

To solve the model we proceed in two steps. First, we compute the equilibrium intensities of finding a counterparty of each agent type. These intensities depend endogenously on the central bank's holdings of the assets. Second, in equilibrium, the agents agree to trade whenever there are potential gains from trade. Prices and lending fee (or specialness) that agents negotiate reflect the degree of search frictions, among other aspects of the market. We use the calibrated model to quantify the relative contribution of risk increase and central bank purchases on specialness and market liquidity and as result on the cash premium running comparative statics simulations.

We should emphasize, however, that the aim of this exercise is not to match the observed specialness and market liquidity of 10-year on-the-run bonds. The model, in fact, cannot fully address phenomena as squeezes on specialness, that we will document later, because it is stationary. We do not model explicitly these phenomena because they lie beyond the scope of this paper. Our model aims at specifically capturing the effect of central bank purchases on specialness and market liquidity and our predictions would be robust to the inclusion of these additional channels.

Finally, we abstract from counterparty risk. One could argue that counterparty risk can reduce lenders' willingness to supply collateral or short-sellers' incentives thereby affecting specialness (Liu and Wu, 2017).³⁴ We do not pursue this line of modeling because the largest majority, up to 90%, of the current repo transactions on the MTS Repo platform is CCP-cleared, as previously discussed in Section 2. Thus, the observed rates (prices) are not affected by counterparty risk, but only by the risk of the underlying collateral.³⁵

³⁴Liu and Wu (2017) extend the Vayanos and Weill (2008) model considering counterparty risk, as the possibility that the short-seller (or borrower) may not deliver the asset, alternatively the lender might not repurchase the asset at the termination of the repo contract. In the first case, the asset may have lost value and hence the short-seller may incur a loss. In the second case, the lender may not be able to regain the asset and the cash collateral posted by the borrower as margins may be worth less than the asset value.

³⁵The model also abstracts from margin requirements. Margin requirements would constrain the positions short-sellers can take because they represent an upfront cost of borrowing a specific asset. Introducing margin requirements would not allow us to rely on the analytical expressions for prices and lending fees derived in Vayanos and Weill (2008).

4.2. Results and empirical predictions

In this section we present the main results arising from our model and draw some testable empirical implications. The model results are reported in Table 3.

[Insert Table 3 near here]

Empirical prediction 1: The specialness of the bond increases with short-selling when asset's risk premium increases.

First, we run the model without the central bank as a buy-and-hold investor. Essentially, we calibrate and solve the Vayanos and Weill (2008) model for the Italian sovereign bond market in non-crisis and crisis times. This allows us to assess the impact of increased sovereign bond risk premia and market liquidity deterioration on specialness. Our model generates empirically plausible effects on specialness. The increase of specialness for the on-the-run asset is of more than 9 basis points compared to the pre-crisis period (see Panel B of Column (1) and (2) of Table 3). The increase in asset's risk premium raises the utility that low-valuation agents derive from a short-selling position and this in turn raises the specialness premium. As in Vayanos and Weill (2008), cash (repo) liquidity can be measured by search times, but these can differ for buyers (lenders) and sellers (borrowers). To condense search times into a one-dimensional measure, we multiply the expected search time for buying an asset by expected search time for selling the same asset.³⁶ These measures are reported in Panel A of Table 3 on a daily basis (see Column (1) and (2)). The market and repo liquidity of the on-the-run bond improves in the crisis period due to the increase in the flow of short-sellers, \underline{F} . However, due to the lower turnover in the cash market (Table 2), the implied cash liquidity measures for the off-the-run assets point to a overall deterioration of market liquidity because the search times increase.

Empirical prediction 2: The specialness of the bond increases with central bank purchases. Central bank purchases activate a scarcity channel which results in an increase in the specialness of purchased bonds.

We introduce the central bank as a high-valuation agent type who buys indistinctively all the assets, both on-the-run and off-the-run. As previously discussed, the central bank has a longer investment horizon because it is less inclined to sell the asset, and it does not lend it in the repo market. In Table 3, Column (3) of Panel A, we report the implied asset

³⁶An agent's expected search time is the inverse of the Poisson intensity of arrival of counterparties. Thus, for a buyer of asset i it is $1/(\lambda\mu_{si})$, and for a seller it is $1/(\lambda\mu_{bi})$.

holdings of the central bank: 35% for the on-the-run assets and 16% for the off-the-run assets. Because the on-the-run asset is more liquid in the cash market due to the presence of short-sellers, the central bank holds a larger share of the on-the-run asset in equilibrium. Our model predicts an increase in specialness from 9.408 to 17.804 basis points due to the scarcity channel affecting the repo market. Since there are fewer lenders, they can extract a higher specialness premium from short-sellers.

To test empirical predictions 1 and 2, our analysis proceeds in three steps. We first run an exploratory analysis using panel regressions in which we regress specialness on the SMP purchases. We follow the identification framework of Eser and Schwaab (2016) and assume that prices and quantities of purchased bonds were not simultaneously determined. This is justified by the implementation framework for the SMP, which required strong coordination among the national central banks and the ECB. Indeed, purchase volumes were predetermined at a daily frequency. In addition, Ghysels, Idier, Manganelli, and Vergote (2016), using intraday data on SMP purchases and yields, show that the level of yields did not affect SMP purchases. We explicitly include regressors that can be linked to demand and supply factors in the cash and repo market. We measure bond market liquidity by using bid-ask spreads. Finally, to quantify the sensitivity of specialness to the underlying asset risk, we control for Italian sovereign CDS.

Second, Figure 1 shows that specialness increased on average for all bonds but its distribution became more skewed with a fatter tail during the crisis period. To analyze this feature we model empirically the full distribution of specialness as a function of our explanatory variables. We estimate the distribution semi-parametrically using quantile panel regressions to assess whether the variables identified in the model as drivers of specialness affect the upper quantiles of the distribution of specialness.

Finally, in order to explore the dynamics of the impact of asset purchases, we turn to a different methodological approach and estimate a structural panel VAR with the same set of regressors. In this way, we can explicitly consider possible endogeneity between specialness and SMP purchases as Ghysels, Idier, Manganelli, and Vergote (2016) do for yields. Our model has been explicitly designed to characterize the effects that a change in SMP purchases has on specialness. The VAR framework allows to test this. Second, we explicitly account for credit risk that could have affected ECB interventions in the crisis period although the central bank does not respond to an increase in asset risk premia in our theoretical framework. Our model establishes a risk short-selling channel: an increase in assets' risk premia should lead to an increase in demand of short-selling and as result an increase in specialness. We can explicitly test the existence of this channel relying on the impulse response functions of the VAR estimates.

Empirical prediction 3: The special bond in which short-selling is concentrated demands a cash premium, a higher price (or a lower yield) relative to a comparable bond. At the same time, its bond market liquidity deteriorates when purchased by the central bank.

In the model by Vayanos and Weill (2008), the asset in which short-selling is concentrated trades at a cash premium for two reasons. First, it has a larger pool of buyers, it is easier to sell and thus it carries a liquidity premium. Second, because holders of the bond can lend it to short-sellers for a fee, it also carries a specialness premium. Therefore, the cash premium results from positive liquidity and specialness premia. All these premia are affected by introducing a central bank purchasing large amount of assets. In this case, the bond becomes locked away in the portfolio of the buy-and-hold central bank effectively decreasing the bond's supply. As a result, the bond market liquidity decreases, but specialness of the same bond increases since it becomes scarcer in the repo market and becomes more valuable for the bond holders. These two effects impact the cash premium in opposing directions. We solve the model assuming that the central bank buys only the on-the-run asset on which short-selling is concentrated. We compare the results of this scenario with the crisis scenario in which the central bank does not buy any asset. The bond market liquidity of the on-the-run asset deteriorates because the expected search time of a trade increases from 0.274 to 0.281 days (Column (4) of Table 3). At the same time, specialness substantially increases from 9.408 to 18.724 basis points. The output of our calibration exercise shows that the scarcity effect prevails and therefore we should observe a positive cash premium for the on-the-run bond. In fact, the cash premium increases from 23.015 to 56.641 basis points.

To test this empirical prediction, we regress measures of cash premia, liquidity premia and short-selling premia on the SMP purchases and show that the results are consistent with model predictions. We also provide a narrative and a descriptive analysis of the patterns observed during the same period in the cash, futures and repo markets for the Italian 10-year on-the-run sovereign bonds. We show that trading strategies potentially involving all these markets fueled the demand for on-the-run bonds and compounded on the scarcity effects induced by the SMP purchases.

5. Results

In Section 4 we have derived three empirical predictions and, in this section, we test them. In Section 5.1 we focus on empirical predictions 1 and 2 focusing on the dynamic relations between credit risk, short-selling demand and SMP purchases and the impact of

these variables on specialness. In Section 5.2 we test the empirical prediction 3 focusing on the Italian 10-year sovereign bonds deliverable for the futures markets.

5.1. *Specialness: Short-selling, credit risk and SMP purchases*

5.1.1. *Panel regressions*

We estimate daily OLS panel regressions with bond fixed effects.³⁷ We estimate a pooled fixed-effects panel regression specification as:

$$S_{i,t} = \beta_1 S_{i,t-1} + \beta_2 X_{i,t-1} + \beta_3 \tilde{X}_{i,t} + \alpha_i + \varepsilon_{i,t}, \quad (4)$$

where $S_{i,t}$ is the specialness of bond i on day t . All the main explanatory variables are lagged by one period (day). $X_{i,t-1}$ contains time-varying bond-specific controls: repo imbalance, cash imbalance, security lending supply, bid-ask spread and bond-specific Italian sovereign CDS spread.³⁸ CDS bond spreads also account for time variation in the data. Bond time-to-maturity and the dummy variables for bond auctions, $\tilde{X}_{i,t}$, are contemporaneous to the dependent variable. The bond fixed effects, α_i , ensure that all bond-specific characteristics are accounted for, provided that they are invariant over time. All the explanatory variables that we include in the regressions have little correlation with each other (see correlation matrix reported in the Online Appendix). We test for unit roots across the panel using a Fisher-type Augmented Dickey-Fuller test and we reject the null hypothesis that our main variables are unit root processes (see results of the test in the Online Appendix). Standard errors are clustered at the bond level.

Table 4 shows the results of panel estimates as in Equation (4) for the full sample (Column (1)) and the three sub-periods (Columns (2) – (4)). The estimation is carried out on the sample of repo transactions *spot next* and *tomorrow next* because we want to pin down the channels of transmission between the cash and the repo market.

[Insert Table 4 near here]

The coefficient of repo imbalance is positive and statistically significant for all the periods, except in the last one. Thus, security-demand in the repo market affects specialness in normal times, but more so in times of stress, when short-sellers are willing to pay very high premia

³⁷As the descriptive statistics show, many values of the specialness are zero or very close to it (see Table A-I in the Appendix). Thus, specialness is a truncated or limited dependent variable. To address this issue, we have run similar analysis using Tobit panel regressions. The results are very similar and available on request. We report results obtained with OLS panel regressions because they allow an easier comparison with the previous literature.

³⁸Bond-specific Italian sovereign CDS spreads are in logarithms to ensure stationarity.

to get hard-to-find securities. During crisis, a 1% increase in repo imbalance has an impact which is more than six times compared to the impact during pre-crisis period. The results suggest a strong role for security-specific demand - linked to short-selling activities - as a determinant of specialness. This is consistent with the empirical prediction 1 derived from our model, in particular when asset risk premia increase.

Consistently with the previous literature (Duffie, 1996, Jordan and Jordan, 1997 and Vayanos and Weill, 2008), we find also that specialness is related to variables reflecting the supply of a specific security. Securities available for lending, our proxy for the amount of a security available in the market, is negatively related to specialness. The coefficient is always statistically significant except in the last period. This suggests also that collateral re-use and specialness are negatively correlated. Turning to the coefficient of the auction dummy, the occurrence of a new auction negatively affects specialness (Sundaresan, 1994). This effect is almost double than average during the crisis period, pointing to significant supply restrictions when the bond is in high demand in the repo market due to increase in Italian sovereign bond risk premia.³⁹ Therefore, specialness is high before a new auction takes place consistent with the idea that short-selling positions in newly-issued bonds are covered through reverse repos thus contributing to making the auctioned bond special (Duffie, 1996). Previous literature on this topic (Nyborg, Rydqvist, and Sundaresan, 2002, Nyborg and Strebulaev, 2003, Keloharju, Nyborg, and Rydqvist, 2005 and Pasquariello and Vega, 2009) also suggests that the auction size "surprise" - actual auction size minus expected size - may also explain specialness. In fact, specialness could respond to actual or expected short squeezes in the post auction market stemming from pre-auction trading and auction allocations. However, such mechanisms are not relevant in our case because the Italian Treasury always sells the full amount of a newly issued bond thanks to the adopted auction mechanism with a bid-to-cover ratio always larger than one (Beetsma, Giuliadori, De Jong, and Widijanto, 2016). We also observe that the Italian Treasury in few circumstances re-issued *old* bonds - bonds that were off-the-run, potentially benefiting from the lower yield.

The coefficient of the bond time-to-maturity variable is positive but statistically significant only in the first period, suggesting that, especially during crisis times, other determinants become more relevant to explain specialness. The coefficient of the bid-ask spread variable is negative but not statistically significant in all periods, nevertheless suggesting that the more liquid securities tend to be on special consistent with Duffie (1996) and Vayanos and Weill (2008).

³⁹In non-reported regressions we have included the dummy in correspondence of the announcement of a new issuance, typically three days earlier. In this case, the coefficient for the dummy is significant and positive, consistent with the notion that traders take short positions in advance of the auction in order to exploit the liquidity of the on-the-run bonds (Duffie, 1996 and Sundaresan, 1994).

Overall, these first results confirm the empirical prediction that specialness is strongly affected by security-specific demand especially when bond risk premia increase.

Next step is to explicitly include in the estimation the SMP purchases carried out by the ECB during the crisis period (from 8 August to 21 December 2011). Table 5 reports the results of these panel regressions in Columns (1) and (2). The coefficients for the supply and demand variables are robust to the introduction of the new variable SMP purchase (Column (1)). The values of the coefficients and the statistical significance are confirmed. As the table shows, in line with empirical prediction 2, bonds purchased by the ECB were more special. In terms of economic significance, a purchase of 1% of outstanding amount - on average around euro 200 millions (Table 1) - results in almost 5 basis points of higher specialness. This value shows an important economic significance of the effect linked to the purchases, since the ECB acquired significant fractions of the outstanding amounts of several securities. This effect is on top of the impact induced by demand in the repo market, as measured by the coefficient of repo imbalance.

[Insert Table 5 near here]

In Column (2) we exclude from the sample the 10-year on-the-run bonds to verify whether our results are driven by the bonds who became very special. The statistical significance of the coefficients is not affected except for the security-specific demand. This suggests that short-selling activity was indeed concentrated on these bonds.

As we have noticed already in Section 3, the crisis period was characterized by a significant increase in the dispersion of specialness. This suggests that the impact of determinants of specialness is not constant across the distribution, but they vary across the quantiles. Thus, we run quantile panel regressions using the same explanatory variables and follow the methodology proposed by Canay (2011). Results are reported in the last two columns of Table 5 for the crisis period and for the highest quantiles (70th and 90th).⁴⁰

The quantile panel regressions show that credit risk, repo imbalance and SMP purchase variables identified in the model as key drivers of specialness explain the differences across the quantiles of the distribution of specialness. In particular, the coefficients associated with these variables increase for the highest quantiles, suggesting a higher impact for the upper tail consistent with our model predictions.

All in all, these results show that large bond purchases by the ECB in the cash market have an impact on the premium paid on these securities in the repo markets. The effect

⁴⁰We are not aware of a procedure to cluster the standard errors when using quantile panel regressions. Therefore, the standard errors tend to be smaller than the standard errors estimated in the OLS panel regressions.

is economically significant (almost 5 basis points for a purchase of 1% of the outstanding amount). The increase in the dispersion of the specialness distribution points out also to some heterogeneity in the effects across securities. In the next sections we will try to pin down the role that a decrease in available supply and an increase in security-specific demand, linked to short-selling, may have had in affecting specialness, bond market liquidity and security lending in a dynamic setting.

5.1.2. Panel VAR

To examine more accurately the relation between SMP purchases, credit risk, repo demand, specialness, market liquidity and collateral re-use, we estimate a panel VAR with daily frequency using the entire portfolio of bonds that were purchased under the SMP. We consider a 7-variable panel VAR represented by the following system of linear equations:

$$Y_{i,t} = A_1 Y_{i,t-1} + A_2 Y_{i,t-2} + \dots + A_p Y_{i,t-p} + B X_{i,t} + u_i + e_{i,t} \quad (5)$$

where $Y_{i,t}$ is the vector of dependent variables; $X_{i,t}$ is a vector of exogenous covariates; u_i and $e_{i,t}$ are vectors of security fixed effects and idiosyncratic errors, respectively. We consider the following dependent variables: CDS bond⁴¹, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending. For all the specifications, we control for the auction date with dummy variables. We estimate the model in first-difference to ensure stationarity and over the crisis period, 8 August - 21 December 2011. The lag length is set to two based on the Schwarz SIC information criteria.

For identification we first rely on a Choleski decomposition and then carry out a series of robustness checks. In the baseline specification we order the variables as follows: CDS bond, cash imbalance, bid-ask spread, SMP purchases, repo imbalance, specialness and available for lending. We assume that shocks to SMP purchases have a contemporaneous impact on repo imbalance and specialness, but shocks to repo imbalance and specialness impact SMP purchases only with a lag. Shocks to cash imbalance and bid-ask spread affect contemporaneously SMP purchases. This setup takes into consideration that the ECB may have reacted to developments in the cash market. Shocks to repo imbalance have a contemporaneous impact on specialness, but shocks to specialness impact repo imbalance only with a lag.

We couch our main results in the form of cumulative impulse response functions (IRFs) and focus our discussion on significant responses. Bootstrapped 90% confidence intervals are based on 1,000 replications. Figure 2 shows selected cumulative IRFs, where each Panel

⁴¹We refer to the variable CDS bond as the bond-specific CDS spread.

corresponds to a different shock.⁴²

[Insert Figure 2 near here]

Using this framework we investigate empirical prediction 1, testing whether the increase in credit risk increases short-selling demand and as result an increase in short-selling induces higher specialness. Panel A shows the effect of a CDS bond shock of 1% on the repo imbalance. The estimated response is positive and statistically significant: a CDS bond shock increases short-selling, consistent with empirical prediction 1. In Panel B we report the cumulative IRF relative to shocks to security-specific demand. A positive shock of 1% to the repo imbalance has an immediate positive impact on specialness. The impact lasts for few days. The average impact is around 5 basis points and it is economically significant. In Panel C we report the cumulative IRF of a CDS bond shock to specialness. The figure shows that an increase of CDS bond does not lead to an increase in specialness, so specialness is not induced by increase in credit risk. Thus, Panel A-C validate the first implication of our model and supports the risk short-selling channel as a driver of the relation between credit risk and specialness. An increase of credit risk leads to an increase in short-selling demand and this leads to an increase in specialness. Credit risk does not directly affect specialness.

Turning to our empirical prediction 2, Panel D shows the effect of a purchase shock of 1% of outstanding amount on specialness. A purchase shock increases the level of specialness (right-hand plot) on average for all purchased bonds, of around 4 basis points at the peak, after around 3 trading days, consistent with the difference in timing induced by delivery and settlement in the cash and repo markets. The size of the peak response is in line with the results of the panel OLS regressions. The impact on specialness is always significant and persistent over 15 days, suggesting a long-lasting effect.

The results also provide evidence that SMP purchases do not respond to specialness shocks, which again supports our prior that the central bank did not react to developments in the repo market (Figure A-IX in the Appendix). However, we observe that shocks to CDS bond have a positive impact on SMP purchases suggesting that the ECB responded to increases in credit risk (Figure A-IV in the Appendix) although our model abstracts from this channel. Finally, shocks to CDS bond induce lower bond market liquidity consistent with the results of Pelizzon, Subrahmanyam, Tomio, and Uno (2016) who examine the dynamic relation between credit risk and liquidity in the Italian sovereign bond market during the same time period that we analyze. They provide evidence that credit risk drives the liquidity of the market, in particular when the CDS spread exceeds 500 bp (Figure A-IV

⁴²We report the complete set of cumulative IRFs in the Appendix.

in the Appendix). At the same time, SMP purchase shocks do not affect bid-ask spreads on average (Figure A-VII in the Appendix).

To assess the robustness of our results, we perform three types of checks: (1) consider alternative ordering of the variables where the SMP purchase variable is ordered last, thus allowing it to respond instantaneously also to repo imbalance and specialness shocks; (2) exclude from the SMP portfolio the 10-year on-the-run bonds to verify whether our results are driven by the bonds who became very special (above 200 basis points); and (3) use the CC&G margins instead of the CDS bond to account for bond risk premia. The results are very similar to those discussed in this section and are presented in the Online Appendix.

We have established a statistically robust relationship between specialness and SMP purchases. Now we proceed to evaluate the economic significance of this impact. We perform a historical decomposition and construct a counterfactual series of average specialness based on the estimation of the structural panel VAR. We replace all realizations of the SMP purchase structural shock with zero, while preserving the remaining structural shocks in the model (Kilian and Lütkepohl, 2017). This counterfactual series shows how specialness would have evolved in the absence of SMP purchases. Figure 3 plots the average specialness of bonds purchased under the SMP and the historical counterfactual of specialness. In the same figure, we also plot the SMP purchases rescaled by outstanding amounts on a weekly basis. The figure shows that the deviation between observed and counterfactual specialness is positive throughout the sample, suggesting a long-lasting effect during the crisis period. Finally, the same figure also suggests that this deviation broadly co-moves with SMP purchases.

[Insert Figure 3 near here]

The effects of SMP purchase shocks are economically significant: on average SMP purchase shocks explain around 27% of specialness, but at times they account for up to 70%. The magnitude is comparable with that obtained in our calibrated exercise. In fact, Column (3) of Table 3 indicates that specialness should increase on average from 9.4 to 17.8 basis points due to central bank purchases in crisis times. This indicates that overall central bank purchases explain almost 50% of specialness in steady state given the model is stationary. So overall our VAR results are in line in terms of the SMP contribution to specialness with the results of the calibrated model.

5.2. On-the-run bonds: Specialness, bond market liquidity and cash premium

Turning to empirical prediction 3, we investigate how the concentration of short-selling activity and SMP purchases on the Italian 10-year on-the-run sovereign bonds is linked

to the cash premium at which they trade, their bond market liquidity and specialness. We focus on these benchmark bonds because they are very liquid securities in which short-selling concentrates. Moreover, they are also part of the deliverable basket underlying long-term futures contracts on Italian sovereign bonds.

We compute the cash premium from a trading strategy composed of a duration-adjusted long position in the 10-year off-the-run bond and a short position on the 10-year on-the-run bond (Krishnamurthy, 2002). We construct this position using daily bond prices and durations from our dataset during the crisis period (see Section B of the Appendix). The on-the-run bonds are the two 10-year benchmark bonds that were on-the-run during the period of the SMP purchases (ISIN IT0004695075 and IT0004759673).⁴³

We estimate panel regressions to formally test how the cash premium is related to specialness and SMP purchases. Thus, we regress the daily estimates of the cash premium on one-day lagged specialness and SMP purchases. We also control for credit risk using the one-day lagged Italian sovereign CDS bond spread and the auction cycle. Specialness and SMP purchases are included as the difference between the SMP daily purchases (specialness) of the on-the-run and the off-the-run bonds. Column (1) of Table 6 reports the estimated coefficients. We find a positive relation between cash premium and specialness consistent with previous evidence of this phenomenon both in the US Treasury market (see for example Amihud and Mendelson, 1991, Jordan and Jordan, 1997, Krishnamurthy, 2002, Goldreich, Hanke, and Nath, 2005, Pasquariello and Vega, 2009, Banerjee and Graveline, 2013 and D'Amico, Fan, and Kitsul, 2018⁴⁴) and in other countries (see for example Boudoukh and Whitelaw, 1991, Boudoukh and Whitelaw, 1993 and Buraschi and Menini, 2002).

[Insert Table 6 near here]

Cash premium and SMP purchases are also strongly positively correlated as implied by the model predictions. A 1% increase in SMP purchases is associated with a 2.5 basis points increase in cash premium. Thus, our results are also consistent with D'Amico, Fan, and Kitsul (2018) who find that the relation between specialness and cash premium is significant on the days of the Fed operations and for securities eligible for the Fed purchases, suggesting that specialness passes through to Treasury cash market prices, providing additional evidence in favor of the scarcity channel of quantitative easing (see for example Krishnamurthy and Vissing-Jorgensen, 2011 and D'Amico and King, 2013).

A strand of empirical literature has shown that on-the-run bonds demand a cash premium because they are significantly more liquid than their off-the-run counterparts (Jordan and

⁴³The 10-year off-the-run bond has the ISIN code IT0004634132.

⁴⁴D'Amico, Fan, and Kitsul (2018) find that this premium is significantly stronger on the days of the Fed operations and for securities eligible for the Fed purchases.

Jordan, 1997, Krishnamurthy, 2002, Buraschi and Menini, 2002, Sundaresan and Wang, 2008 and Graveline and McBrady, 2011). Vayanos and Weill (2008) provides a rationale for this empirical link. Short-selling activity drives both the superior liquidity of on-the-run bond and its specialness. This mechanism, however, does not work when the available supply of on-the-run bonds severely decreases due to central bank purchases. Because the bond becomes locked away in the central bank buy-and-hold portfolio, the pool of potential buyers decreases, thus negatively affecting the liquidity of the bond. We test this outcome by regressing the bid-ask spread differential between the on-the-run and off-the-run bonds on SMP purchases. Column (2) of Table 6 reports the estimates. The coefficient associated with SMP purchases confirms a strong and robust negative relation. When the ECB bought large amounts, on-the-run bonds became relatively more illiquid than their equivalent off-the-run. A 1% increase in SMP purchases is associated with more than 2 basis points increase in bid-ask spread differential.

This evidence suggests that the positive cash premium enjoyed by on-the-run bonds derives from the scarcity premium in the repo market and ultimately from interaction between short-selling and SMP purchases as the model predicts. To measure the contribution of short-selling activity on the cash premium, we rely on the approach by Banerjee and Graveline (2013). They decompose the cash premium in two components, the net premiums paid by long-term investors and short-sellers. The intuition is as follows. Short-sellers pay the financing premium entering a reverse repo transaction that ensures them the delivery of the bond they sold. Banerjee and Graveline (2013) show that a positive net premium paid by short-sellers can be sustained when there are very long-term investors, like central banks, that forgo the special premia they can earn by lending out their bonds and recover almost none of the price premium they pay for taking long positions in on-the-run bonds. In Section B of the Appendix we provide a derivation of the decomposition and discuss how we compute the short-selling premium in our case.

We regress the short-selling premium on specialness and SMP purchases. Results are reported on Column (3) of Table 6. The empirical evidence is consistent with our model predictions, as the cost of short-selling increases with specialness and SMP purchases. Short-sellers paid positive net premia. The long position held by the ECB allowed this premium to be sustained in the market, since the central bank was not interested in cashing in the large premium by making the securities available again for trading. Therefore, the cash premia at which the on-the-run bonds were trading during the crisis period resulted from scarcity of bonds in the repo markets as opposed to bond market liquidity premia.

In the rest of this section, we analyze some descriptive patterns of the 10-year on-the-run bonds and provide some narrative on why short-selling concentrated on these bonds. Figure

4 shows the short-selling premium, as implied by the Banerjee and Graveline (2013) decomposition, for the two bonds that were on-the-run in the period from August to December 2011. It also shows the difference between the SMP purchases of these bonds and the closest off-the-run bond. The short-selling premia are hovering around zero with a positive average annual return of 2.10 and 7.24 basis points for the first and second 10-year on-the-run respectively. However, they reached high positive levels in few circumstances. In particular, the premium of the first on-the-run bond reached 100.84 basis points in the second week of September, when the SMP reached the highest level of holdings for that same bond. This week coincided with the delivery date of futures contract, 10 September 2011, highlighted by the vertical line.

[Insert Figure 4 near here]

The dynamics observed in the cash and in the repo markets for sovereign bonds are also linked to the markets for futures contracts written on government bonds. Indeed, the simultaneous trading of futures contracts and of their underlying, the *basis trading*, represents an important part of transactions driven by short-selling activity in the repo markets (Choudhry, 2007). Figure 5 shows the net basis of the long-term Italian futures contracts between July and December 2011, when there were two delivery dates, in September and in December (represented by the vertical lines).

A key feature of a futures contract is that the seller can deliver any bond from a basket of deliverable bonds.⁴⁵ One of the deliverable bonds is identified as the cheapest-to-deliver (CTD) and it is the bond that futures sellers are most likely to deliver. Ahead of the two delivery dates, the two CTD bonds were the two 10-year on-the-run bonds whose specialness, bond market liquidity and cash premium we have just analyzed. For the September delivery, the bond with ISIN IT0004695075 is the CTD bond with a lower basis than the average basis of the other deliverable bonds. With the issuance of a new on-the-run bond short-sellers moved to this bond (ISIN IT0004759673) who became the newly CTD bond for the December delivery.⁴⁶

Figure 5 shows the net basis for the two CTD bonds and for the average of the other deliverable bonds. The basis is on average positive suggesting the following trading strategy. The arbitrageur lends funds to borrow the bond in the repo market and shorts it in the cash market. At the same time, he/she takes a long position in the futures contract. As

⁴⁵The contract terms of the Italian long-term futures contract specify that a delivery obligation arising from a short position is only fulfilled by the delivery of coupon-bearing debt securities with a remaining life of between 8.5 and 11 years and an original maturity of no longer than 16 years.

⁴⁶This bond was issued on 1 September 2011 and it became the newly 10-year on-the-run bond.

the contract approaches maturity, the net basis converges toward zero.⁴⁷ On delivery date, the bond is delivered to the arbitrageur in which he/she has a long position, and this also enables him/her to close-out the repo trade. Around that date, we expect the bond to be in high demand in special repo markets and/or in securities lending markets.

[Insert Figure 5 near here]

Figure 6 shows all the important measures related to the first 10-year on-the-run bond (ISIN IT0004695075): specialness, repo imbalance and the SMP purchases (as percentage of the outstanding amounts).⁴⁸ We depict the same variables for the second 10-year on-the-run bond (ISIN IT0004759673) in Figure A-XI of the Appendix. The top panel of Figure 6 shows that after the re-activation of the SMP on 8 August 2011 specialness of the 10-year on-the-run bond started to increase and it reached more than 400 basis points after few weeks in correspondence of the September futures delivery date and closely following the SMP purchases. Interestingly, the bond was not replaced as CTD by another bond of the deliverable basket although it became very special close to the delivery date. Then, the specialness remained at that level for some time. The bottom panel of Figure 6 shows the pattern of repo imbalance. During the first part of our sample, when the ECB was purchasing bonds at a sustained pace, repo imbalance was generally positive. More traders were initiating reverse repos versus financing repos, possibly due to the need to cover short positions associated with futures contracts. Pelizzon, Subrahmanyam, Tomio, and Uno (2014) find significant support for this documenting that the ECB purchases had a significant impact on the deviation of arbitrage relationship between the cash and futures markets for the 10-year Italian sovereign bonds. Our previous findings of a deterioration in bond market liquidity of the 10-year on-the-run bonds when purchased by the ECB are clearly important for the price-discovery mechanism between the cash and futures markets. A larger bond bid-ask spread would lead to a larger range of possible relative cash bond prices when compared with the futures prices leaving market participants uncertain on the true price (see also Pelizzon, Subrahmanyam, Tomio, and Uno, 2018).⁴⁹

[Insert Figure 6 near here]

An alternative for borrowing securities to repo markets are the securities lending markets. Figure 7 plots the security lending fee for the first 10-year on-the run bond. The lending

⁴⁷The delivery date is the tenth day of September and December. If the tenth day is a holiday, the delivery date is the next business day. However, the last trading date is two business days before the delivery date.

⁴⁸We do not report the SMP purchase amounts given data confidentiality.

⁴⁹Pelizzon, Subrahmanyam, Tomio, and Uno (2018) document that bond purchases carried out in the context of quantitative easing program by the European Central Bank created a large mispricing between the market for German and Italian government bonds and their respective futures contracts.

fee tracks very closely the specialness of the bond as presented in Figure 6. The cost of borrowing the bond dramatically increased around the futures delivery. Figure 7 also plots the active utilization of the bond defined as loaned bonds divided by available bonds in the securities lending market. With rising fees to borrow, extremely high utilization rate suggests that short-sellers were very active in searching for the bond.

[Insert Figure 7 near here]

6. Implications for asset delivery and collateral use

6.1. *Fails-to-deliver*

The key feature of a special repo transaction is that short-sellers have to deliver the asset they borrowed. The prevalence of the delivery constraint is illustrated by the incidence of short-squeezes in specialness, whereby short-sellers have difficulty delivering the asset they borrowed. In these circumstances, when short-sellers are unable to find the bond, or not willing to pay the high specialness premium they may also decide to fail on the delivery. Previous literature has investigated these effects mainly on the stock market (Evans, Geczy, Musto, and Reed, 2009 and Fotak, Raman, and Yadav, 2014). Some evidence for the US Treasury market is provided in Fleming and Garbade (2005) and more recently in Fleming, Keane, Martin, and McMorrow (2014). They document that traders in the US market fail to deliver when specialness becomes high, even if they incur in penalties.

During the spring and summer of 2011, the number of fails-to-deliver on transactions involving Italian sovereign bonds as underlying notably increased (Banca d'Italia, 2011) and were not limited to the 10-year on-the-run bonds. To shed light on the determinants of these fails-to-deliver, we estimate a Probit model of the probability of fail-to-deliver at time $t + 3$ and a OLS model on the nominal amount of fails over the traded amount at time $t + 3$ with bond fixed effects. We estimate the following model:

$$Y_{i,t+3} = \beta_{1,i}Z_{i,t} + \beta_{2,i}X_{i,t} + \alpha_i + \varepsilon_{i,t}, \quad (6)$$

where $Y_{i,t+3}$ is either i) dummy variable equal to one when a fail-to-deliver of bond i at day $t + 3$ occurs (for the Probit); ii) nominal amount of fail-to-deliver (over nominal amount traded) of bond i at day $t + 3$ (for the OLS). $Z_{i,t}$ is either i) the specialness of bond i at day t ; or ii) the SMP $_{i,t}$ purchase of bond i at date t . $X_{i,t}$ is a set of controls. We choose a lead of three days for the regressions to account for the possibility that a short-seller can

fail-to-deliver the security at time $t + 3$ in a spot next repo contract.⁵⁰

Table 7 reports the results of the estimation. In the first three columns we report the marginal effect estimates for the Probit model. Previous literature has shown that fails to deliver are associated to the premium to be paid to borrow the asset (see for example Evans, Geczy, Musto, and Reed, 2009 and Fotak, Raman, and Yadav, 2014). Therefore, we introduce specialness as explanatory variable and, as expected, the probability of a fail-to-deliver increases with the specialness of the bond. A 1 basis point change in specialness increases the probability of a fail-to-deliver by 0.32% (see Column (1)).

[Insert Table 7 near here]

In response to the increase of fails, Monte Titoli, the central securities depository for the Italian sovereign bonds, replaced the fixed penalty system with a system applying penalties in proportion to the volume of daily fails security by security, valued at market prices. To account for this revision we use a dummy variable, D. Penalties, that is equal to one after the revision went into effect on 1 September 2011.⁵¹ Our estimates suggest that the increase in penalties decreased the probability of a fail-to-deliver by 5.33%.

The other coefficients show that bonds that are in high-demand in special repo markets have a higher probability not to be delivered at settlement. The same applies for older bonds that has a lower turnover compared to younger bonds. Finally, bonds that are available in the security lending market have a lower probability not to be delivered. This result supports our previous findings that access to security lending market, as an alternative to special repo markets for borrowing securities, can mitigate the likelihood of settlement problems.

In Column (2) the sample is restricted to the bonds purchased under the SMP and results are confirmed for specialness, while the coefficient of D. Penalties is not statistically significant but has a negative sign. At the same time, the coefficient of repo imbalance remains statistically significant and it is also higher than the value estimated for the entire sample, suggesting that for bonds that are in high demand in the repo market penalties have a muted effect. Although the introduction of penalties seems to have been effective in mitigating fails on average, we still observe that the volume of fails-to-deliver on the two 10-year benchmark bonds increased dramatically in October 2011 (Figure 8) in concomitance with the significant rises in specialness of the two securities (Figure 6 and A-XI).

⁵⁰Two days is the standard settlement time for the MTS cash market.

⁵¹At the end of August 2011 Monte Titoli announced "Consob and the Bank of Italy's settlement service regulation require Monte Titoli participants to guarantee the availability of cash and securities necessary to finalize settlement of transactions with their counter-parties. This in addition, will allow Monte Titoli to improve the efficiency of the settlement system. A penalties model has been developed to encourage participants to comply with this requirement."

[Insert Figure 8 near here]

To further disentangle the effect of outright purchases, we replace specialness with the SMP purchases (Column (3)). The probability of fail-to-deliver is positively related to SMP purchases. Thus, our results suggest that the SMP purchases ultimately increased the incidence of fails, because the cost of borrowing the bonds in the repo market increased.

We run similar OLS specifications where we regress the nominal amount of fails divided by the nominal amount outstanding at bond level on specialness and on the SMP purchases. The results, reported in Columns (4) – (6), confirm the link between specialness, SMP purchases and fails-to-deliver.

6.2. *Collateral use and central bank funding*

What are the implications of increased specialness on collateral utilization? As we have argued also earlier, special bonds can be pledged as collateral for liquidity at a below-market refinancing rate. We do not have data at the bank holding-bond level to assess what was the impact of the SMP purchases on the value and composition of the portfolios of holders of the bonds targeted by the ECB. However, we can provide some indirect evidence looking at the collateral pledged at the ECB. In Table 8 we estimate panel regressions as in Section 5.1.1 and add as an explanatory variable also the collateral pledged at the ECB at the bond level (as a fraction of the total amount outstanding). The results show a negative correlation between specialness and amount pledged at the ECB. The coefficients are statistically significant for the quantile regressions on the right side of the distribution, i.e. for very special bonds. Banks preferred not to pledge these bonds for the ECB liquidity operations and presumably used these bonds in the private markets, either to get financing at even cheaper rates than the policy rates, or to bring the asset in the repo or securities lending markets and take advantage of the rising lending fees (as Figure 7 suggests for the 10–year benchmark bonds). Overall our evidence is consistent with recent empirical literature documenting how market participants actively manage their collateral portfolio (Aggarwal, Bai, and Laeven, 2018 and Jank and Moench, 2019).

[Insert Table 8 near here]

7. Concluding remarks

In this article we have analyzed how central bank purchases affect specialness and liquidity of purchased bonds, possibly impacting the smooth functioning of bond markets. We have

shown that restrictions to the available supply of a security can interact with short-selling activity and have sizable and persistent effects on its scarcity premium, its liquidity and use as collateral. Our results provide interesting insights for researchers and policy makers interested in the functioning of very liquid financial markets. Our evidence supports the mechanisms linking the cash and the repo markets in models as in Duffie (1996) and Vayanos and Weill (2008) and in particular the role played by short-sellers. At the same time, we emphasize that the relation between specialness in the repo market and liquidity in the cash market is dependent on the available supply of a security and needs to be framed in a dynamic model. If there are shocks to the supply, specialness reflects mainly the scarcity of a certain security and its associated illiquidity. Special bonds trade at a cash premium which can persist especially in markets in which holders of long positions do not lend the security. This relation can persist and eventually result in high premia paid by short-sellers when the long position is unwilling to provide the security back to the market.

Concerning the implications for policy making, our results provide a clear indication of the possible side effects on market functioning of the asset purchase programs of the central banks. It is important to stress that we found economically and statistically significant effects on market segmentation in an environment where transactions costs and other market frictions are minimal. Indeed, our sample consists of transactions taking place on trading platforms, largely cleared by CCPs and therefore with no counterparty risk. We also emphasize the pivotal role that the central bank can play in the security lending market. When assets are scarce, holders of these securities are unwilling to lend them in the private markets, probably for fears that the asset will not be returned timely. Therefore, a policy of promoting security lending by the central bank may be beneficial to support market liquidity and smooth collateral use during these episodes of market stress.

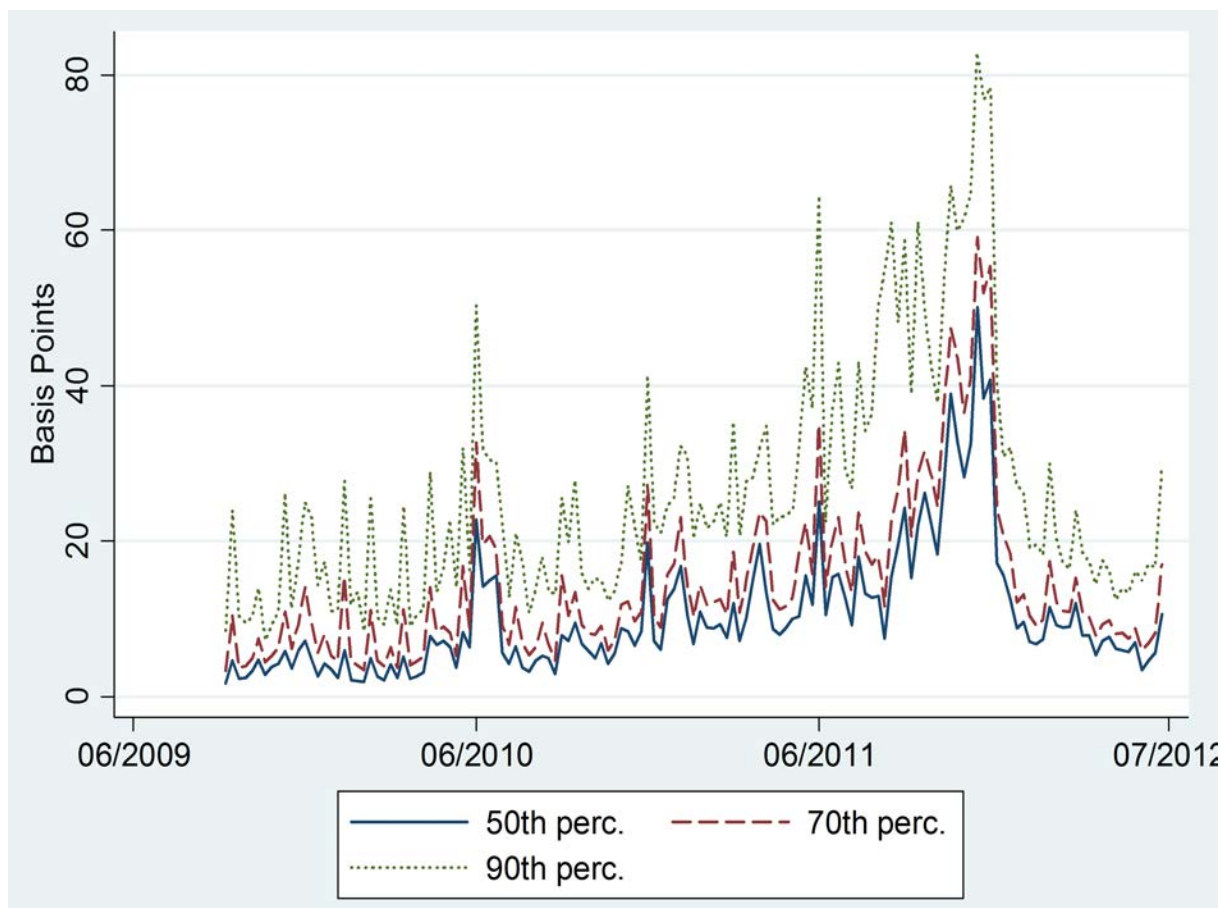


Fig. 1. **The distribution of specialness** - The figure plots the empirical distribution of specialness for the 50th, 70th and 90th percentile. Specialness is calculated as the difference between the general collateral (GC) repo rate and the special repo rate on a specific security and day of trading. The rates refer to repo transactions on underlying Italian sovereign securities as traded on the MTS repo platform from 1 October 2009 to 7 July 2012.

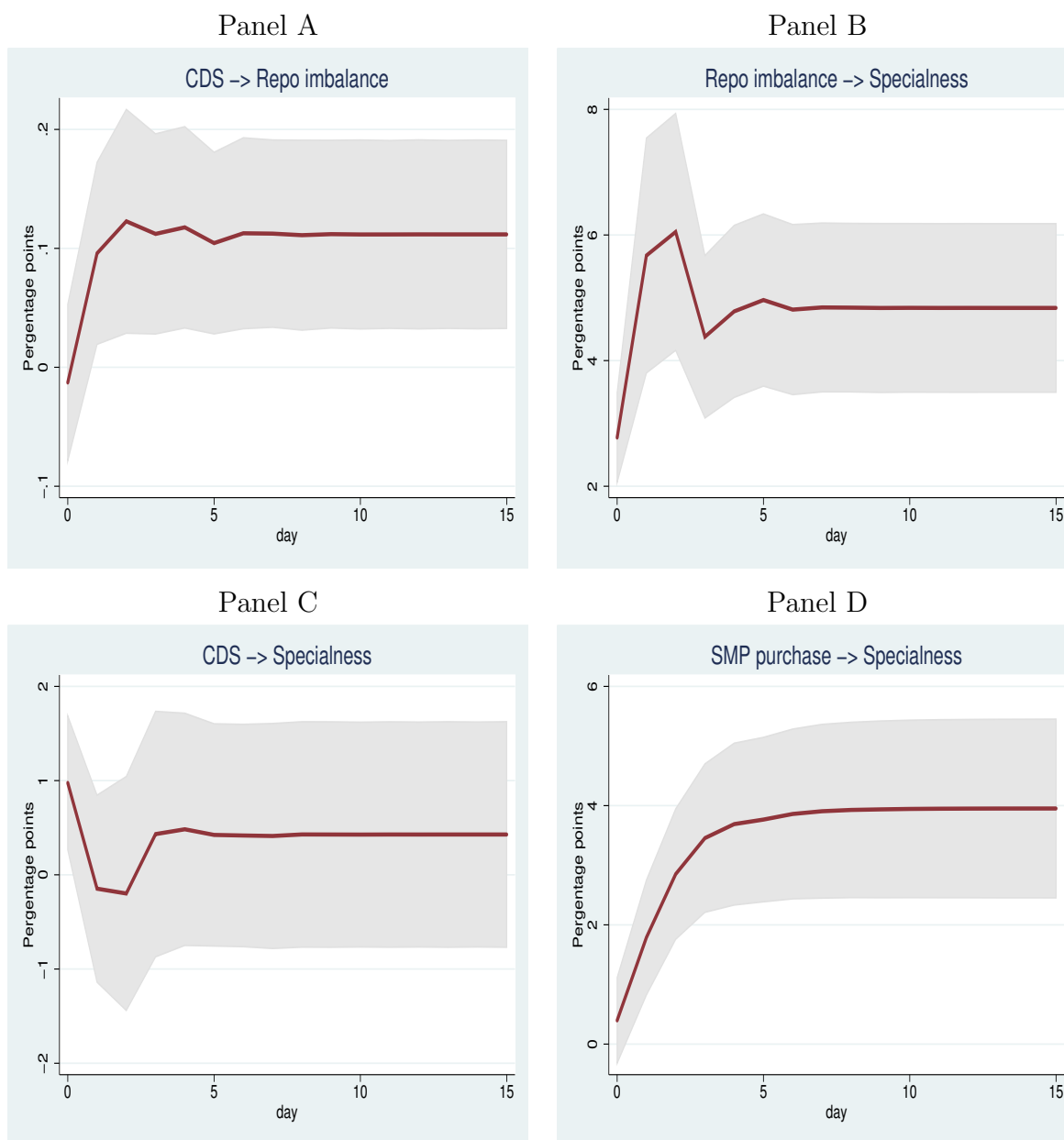


Fig. 2. **Panel VAR Cumulative Impulse Response Functions** - The figure plots the cumulative impulse response functions of (1) repo imbalance to a CDS bond shock of 1% (Panel A); (2) specialness to a repo imbalance shock of 1% (Panel B); (3) specialness to a CDS bond shock of 1% (Panel C); and specialness to a SMP purchase shock of 1% of outstanding amount (Panel D) and 90% bootstrapped confidence intervals (grey dashed lines) based on 1,000 replications. The cumulative impulse response functions are estimated from a panel VAR model in first-difference including the following variables: CDS bond, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending of the bonds purchased by the ECB under the SMP from 8 August 2011 to 21 December 2011.

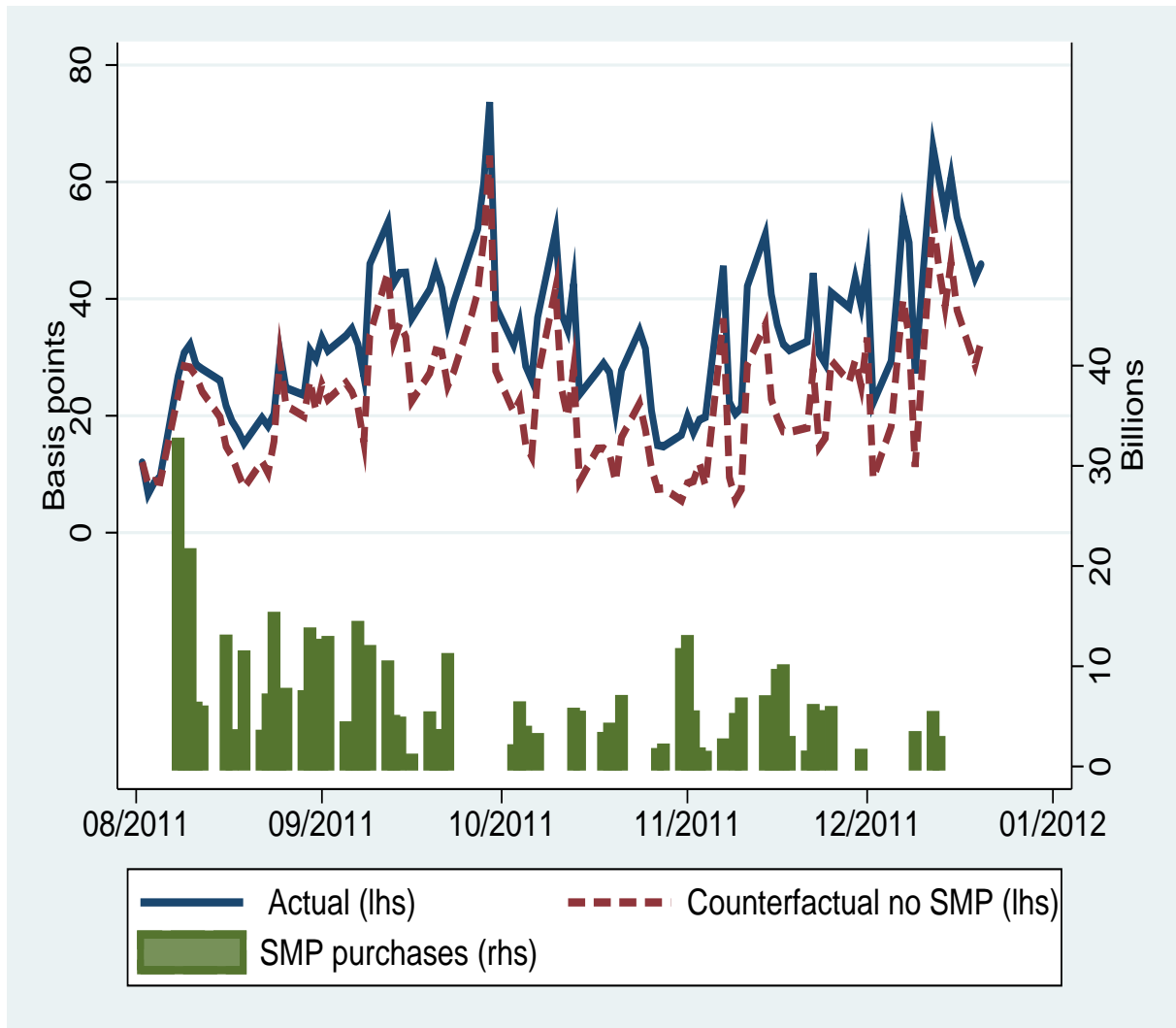


Fig. 3. **Historical counterfactual of specialness** - This figure plots the average specialness of bonds purchased by the ECB under the SMP and the historical counterfactual of specialness in the absence of SMP purchases, based on the estimation of a panel VAR model in first-difference. The model includes the following variables: CDS bond, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending of the bonds purchased under the SMP from 1 August 2011 to 21 December 2011. The counterfactual shows how specialness of the bonds bought under the SMP would have evolved without SMP purchase shocks. It is calculated by replacing all realizations of the SMP structural shock with zero while preserving the remaining structural shocks in the model. The bars indicate the volume of Italian sovereign bonds purchased by the ECB over the same period.

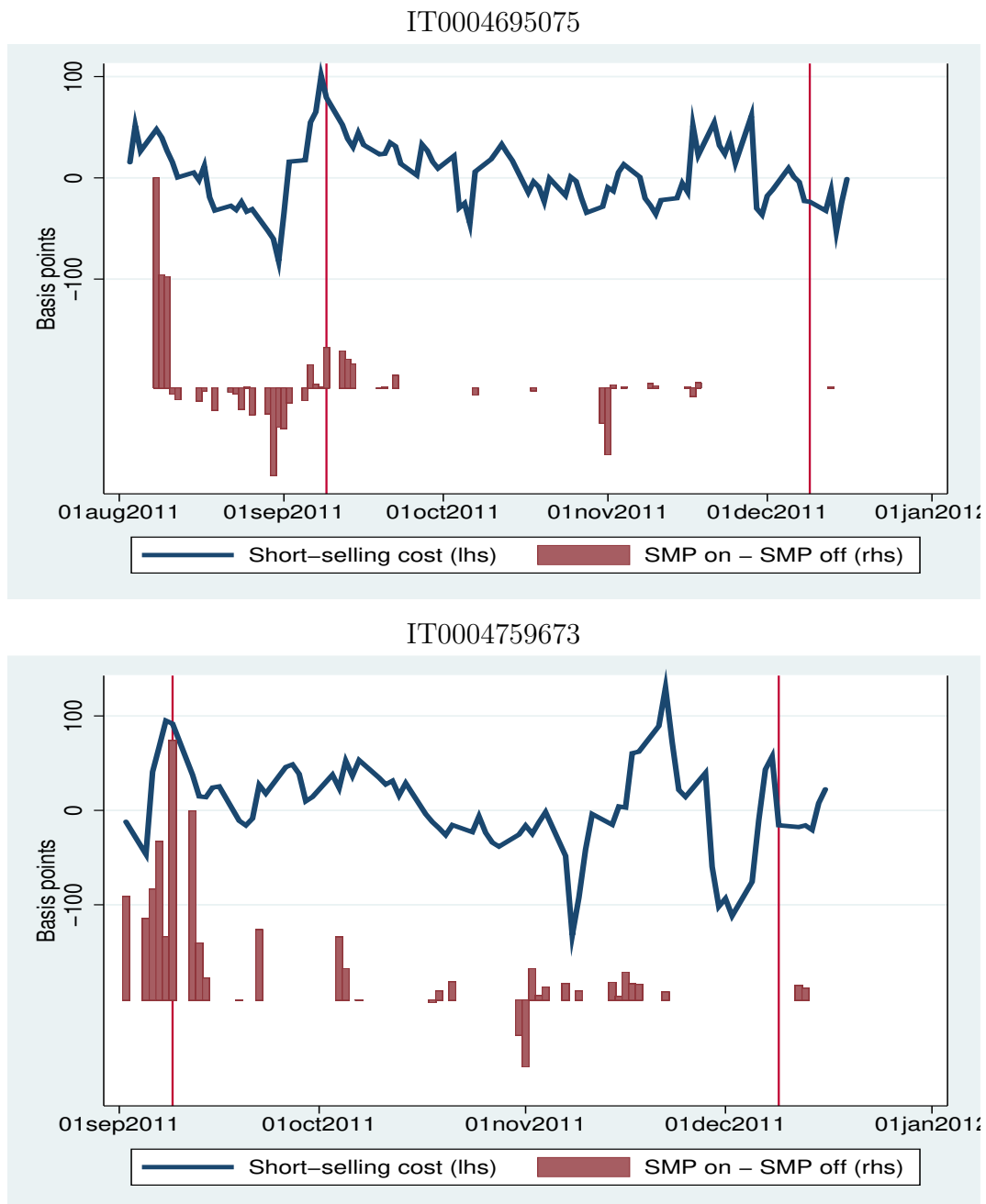


Fig. 4. **Short-selling premium of 10-year on-the-run bonds** - The figure plots the annualized cost of shorting a 10-year on-the-run bond at the daily frequency and taking a duration equivalent long position in the 10-year off-the-run bond. The bars show the difference between the SMP daily purchases of the 10-year on-the-run and the second off-the-run bond. Continuous vertical lines indicate futures contracts delivery dates.

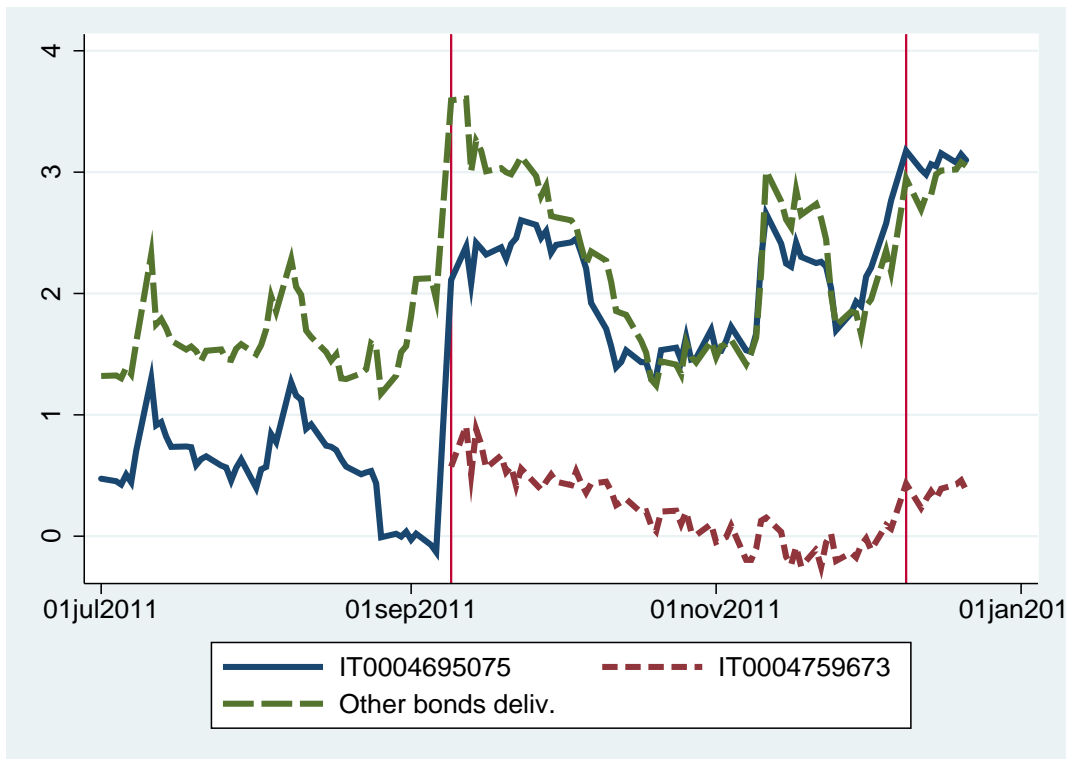


Fig. 5. **Futures net basis** - This figure shows the time series of the net futures basis for different Italian sovereign bonds deliverable for futures contracts maturing in September and December 2011. Continuous vertical lines indicate futures delivery dates. The continuous line represents the net basis of the on-the-run bond (IT0004695075) that was the cheapest-to-deliver bond for the September 2011 futures delivery date. The dashed line represents the net basis of the on-the-run bond (IT0004759673) that was the cheapest-to-deliver bond for the December 2011 futures delivery date. The long-dashed line represents the average net basis of the other deliverable bonds.

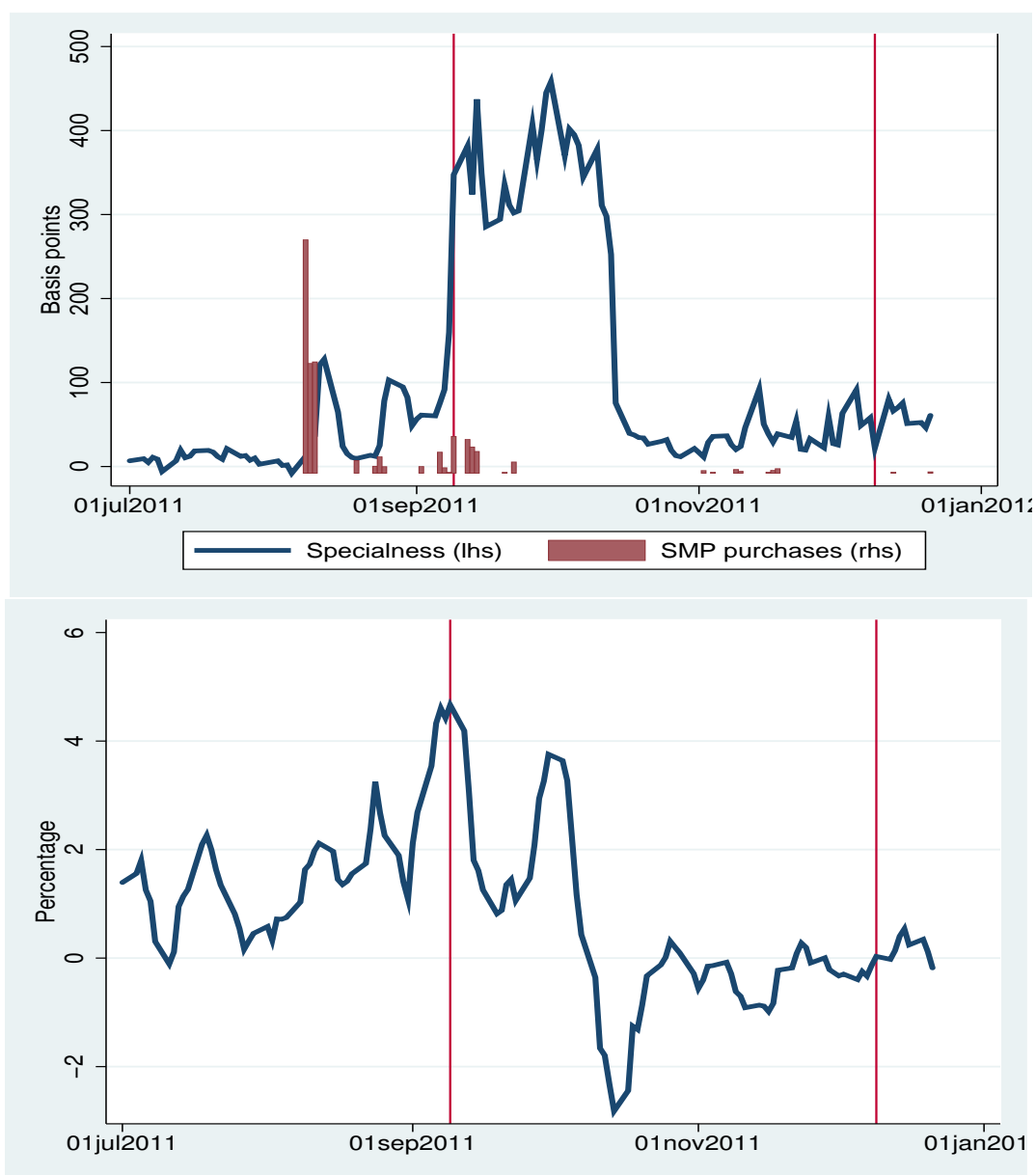


Fig. 6. **Specialness and repo imbalance for the 10-year on-the-run bond (IT0004695075)** - The figure shows the value of specialness (top panel) and of repo imbalance (bottom panel) calculated for the Italian sovereign bond with 10-year maturity (ISIN IT0004695075) that was on-the-run during the period of the SMP purchases. Specialness is calculated as the difference between the general collateral (GC) repo rate and the special repo rate on this benchmark security and it is reported in basis points (left-hand scale). Repo imbalance is the difference between the transactions initiated as special reverse repo and the transactions initiated as financing repo on the 10-year on-the-run security and it is reported in percentage points (left-hand scale). The bars report the value of the on-the-run security purchased in the SMP portfolio. Continuous vertical lines indicate futures delivery dates.

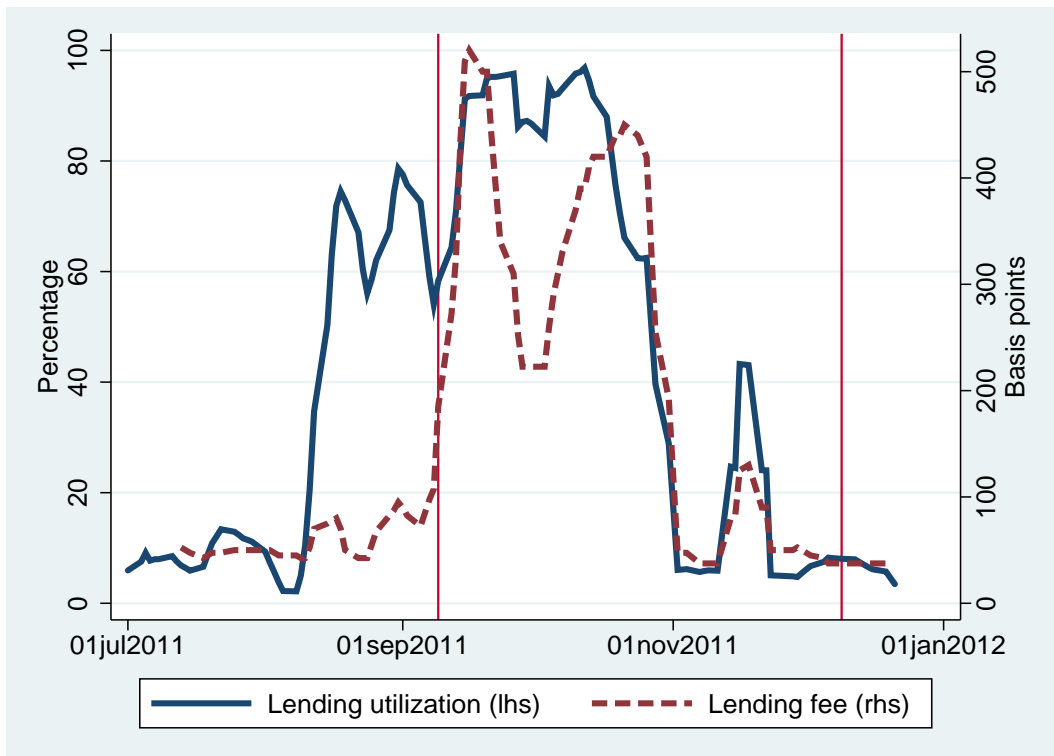


Fig. 7. **Lending utilization and fee of the 10-year on-the-run bond in the securities lending market** - The figure shows the active utilization and annualized lending fee in the securities lending market of the 10-year on-the-run bond (IT0004695075). Active utilization is defined as loaned bonds divided by available bonds in the securities lending market. Continuous vertical lines indicate futures contracts delivery dates.

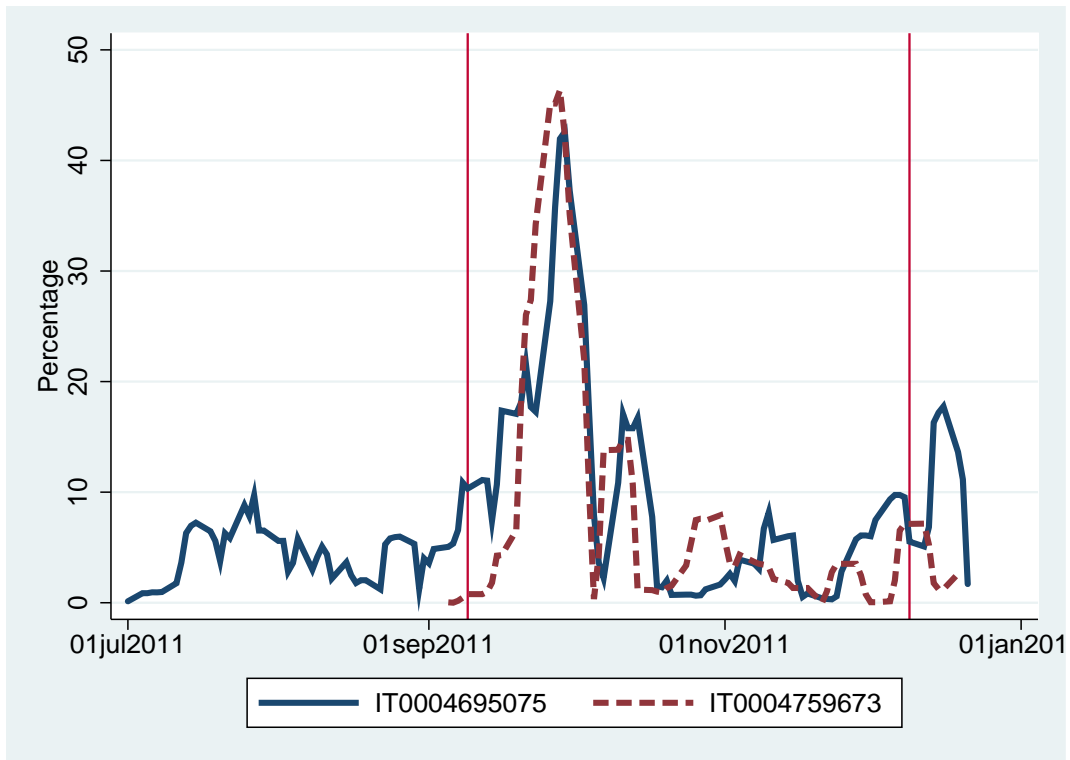


Fig. 8. **Fails-to-deliver of the 10-year on-the-run bond** - The figure shows fails-to-deliver of transactions in bond markets with the 10-year on-the-run bond as underlying. Fails-to-deliver is computed as the nominal amount of fails over the total nominal amount of transactions involving the same security settled by Monte Titoli. Continuous vertical lines indicate futures contracts delivery dates.

Table 1: Descriptive statistics - This table reports the mean and the standard deviation of all the main variables used in the analysis. The statistics are reported for the full sample and for three distinct sub-periods. First period: from 1 October 2009 to 7 August 2011. Second period: from 8 August 2011 to 21 December 2011. Third period: from 22 December 2011 to 12 July 2012. Numbers in parenthesis report the same statistics calculated only on the days when the securities were bought under the Security Market Programme (SMP). Specialness denotes the difference between the general repo (GC) rate and the special repo rate on a specific security and day of trading and is expressed in basis points. Bond nominal outstanding denotes the nominal outstanding amount of a specific security underlying a special special repo transaction, at security level on a daily basis. Repo imbalance denotes the difference between reverse initiated and financing initiated special repo transactions, at security level on a daily basis. Cash imbalance denotes the difference between the aggregate sell and buy initiated volume in the cash market, at security level on a daily basis. Avail. lending denotes the nominal amount available for lending, at security level on a daily basis. Bond time-to-maturity denotes the time-to-maturity of a specific security on a daily basis. Bid-ask spread denotes the bid-ask spread based on BGN Bloomberg prices at or before 5pm, at security level on a daily basis. Cash turnover denotes the total volume over the nominal outstanding amount of the security and expressed in percentage terms. CDS bond denotes the US dollar-denominated CDS spread matched at bond-level using the bond time-to-maturity. CCP margin denotes the margin applied by Cassa Compensazione and Garanzia on MTS repo transactions. Fail-to-deliver denotes the nominal amount of fails over the nominal amount settled by Monte Titoli, at security level on a daily basis. Specialness and repo imbalance are based on tomorrow next and spot next repo transactions. Repo imbalance, cash imbalance and available for lending are re-scaled by the nominal outstanding amount of the security and expressed in percentage terms.

	Mean	St.dev.	Mean	St.dev.	Mean	St.dev.	Mean	St.dev.
	Full sample		1st period		2nd period		3rd period	
Specialness	14.708	24.525	11.967	23.734	29.965 (35.480)	31.762 (38.967)	12.902	15.953
Bond nominal outstanding	15,284	6,476	15,151	6,196	15,632 (20,792)	6,803 (4,785)	15,467	7,079
Repo imbalance	0.094	1.801	0.302	1.763	-0.226 (0.314)	1.802 (1.670)	-0.347	1.806
Cash imbalance	0.003	0.542	0.003	0.568	0.012 (0.037)	0.472 (0.185)	-0.005	0.474
Avail. lending	3.640	3.829	4.272	4.151	3.010 (2.615)	3.047 (1.468)	1.751	1.969
Bond time-to-mat.	6.010	7.477	6.096	7.648	6.025 (5.364)	7.272 (2.735)	5.727	7.048
Bid-ask spread	0.848	5.193	0.766	4.541	0.987 (0.522)	4.740 (0.450)	1.001	7.051
Cash turnover	0.424	0.803	0.466	0.848	0.314 (0.189)	0.636 (0.324)	0.326	0.691
CDS bond	231.998	150.497	137.668	61.090	442.893 (446.310)	83.534 (83.001)	381.683	108.396
CCP margin	3.770	3.467	2.775	2.740	5.217 (5.065)	3.228 (1.987)	6.062	4.267
Fail-to-deliver	2.394	8.357	2.268	8.459	2.577 (2.729)	8.291 (6.518)	2.671	8.057

Table 2: **Parameter values**

Parameters	Definition	October 2009	August 2011
		July 2011 "Non-crisis"	December 2011 "Crisis"
		Value	Value
N	Number of bonds	50	50
S	Supply of each bond	2%	2%
$1/\bar{\kappa}$	Investment horizon of high-valuation agents (years)	0.85	1.33
$1/\underline{\kappa}$	Investment horizon of low-valuation agents (years)	0.09	0.1
$1/\bar{\kappa}^{cb}$	Investment horizon of central bank (years)		10
\bar{F}	Flow of high-valuation agents	1.176	0.643
\bar{F}^{cb}	Flow of central bank		0.016
\underline{F}	Flow of low-valuation agents	0.01	0.1
r	Risk free rate (ECB refinancing rate)	1.11%	1.41%
\bar{x}	Hedging benefit of high-valuation agents	0.15	0.15
\underline{x}	Hedging benefit of low-valuation agents	2.63	2.95
y	Cost of risk bearing	0.73	0.79
δ	Dividend rate	1	1
λ	Contact intensity in spot market	10^6	10^6
ν	Contact intensity in repo market	5×10^4	5×10^4
ϕ	Bargaining power of a buyer	0.5	0.5
θ	Bargaining power of a lender	0.5	0.5

Table 3: Numerical results from model calibration - The table shows the values of cash liquidity for on-the-run and off-the-run assets, repo liquidity for on-the-run asset, cash premium and specialness arising from model calibration under four different scenarios. In Column (1) the results are based on the parameters associated with the non-crisis period (Column (1) of Table 2) with no purchases by the central bank. In Column (2) – (4) the results are based on the parameters associated with the crisis period (Column (2) of Table 2). In Column (2) the central bank does not purchase assets. In Column (3) the central bank, as a high-valuation agent, buys both the on-the-run and off-the-run assets. In Column (4) the central bank, as a high-valuation agent, buys only the on-the-run asset. Panel A reports values for the liquidity in the cash and repo markets of the on-the-run and off-the-run bonds. The equilibrium holdings are re-scaled by the asset supply. The cash liquidity is measured as the product of the expected search time for buying an asset by expected search time for selling the same asset. The repo liquidity is measured as the product of the expected search time for lending an asset by the expected search time for borrowing the same asset. Panel B reports the specialness and the cash premium of the on-the-run asset. Specialness is computed as the ratio of the lending fee ω_1 and the asset price p_1 . The cash premium is computed as the difference between the expected return of the off-the-run asset and expected return of the on-the-run asset, $\delta/p_2 - \delta/p_1$.

	(1) Non-crisis	(2)	(3) Crisis	(4)
		No Central Bank	Central Bank	Central Bank
		Both assets On-the-run asset		
Panel A - Liquidity and CB holdings				
Cash liquidity on-the-run (days)	1.816	0.274	0.280	0.281
Cash liquidity off-the-run (days)	2.658	4.163	4.842	4.164
Repo liquidity on-the-run (days)	7.541	3.903	3.917	3.921
CB on-the-run holdings			35%	35%
CB off-the-run holdings			16%	
Panel B - Specialness and cash premium				
Specialness on-the-run (basis points)	0.183	9.408	17.804	18.724
Cash premium (basis points)	0.820	23.015	51.431	56.641

Table 4: **Specialness** - The table shows the results of OLS panel regressions with bond fixed effects. Specialness is expressed in basis points and is based on spot next (SN) and tomorrow next (TN) transactions. The repo imbalance is based on spot next (SN) and tomorrow next (TN) transactions. The repo imbalance, cash imbalance and available for lending variables are rescaled by the nominal outstanding amount of the bond, expressed in percentage terms and are lagged by one day (see Section 3.1 for details). Bond time-to-maturity denotes the time-to-maturity of a specific security. Bid-ask spread denotes the bid-ask spread based on BGN Bloomberg prices at or before 5pm. D. Auction is a dummy variable to control for the date of a primary issuance of the security. The variable CDS bond is based on the term structure of US dollar-denominated Italian sovereign CDS contracts. Every day we interpolate the term structure of CDS spreads and match the implied CDS spread with the bond with a corresponding time-to-maturity. The CDS bond variable is expressed in logarithmic and lagged by one day. Standard errors are in parenthesis and are clustered by bond identifier. The results are reported for the full period and for the three distinct sub-periods: 1 October 2009 - 7 August 2011, 8 August 2011 - 21 December 2011 and 22 December 2011 - 12 July 2012. Stars denote statistical significance at 10% (*), 5% (**) and 1% (***)).

	(1)	(2)	(3)	(4)
	Full	1st	2nd	3rd
Specialness (lag)	0.867*** (0.030)	0.886*** (0.026)	0.798*** (0.093)	0.817*** (0.028)
Repo imbalance	0.314*** (0.111)	0.194** (0.089)	1.218** (0.507)	0.107 (0.076)
Cash imbalance	-0.256 (0.157)	-0.062 (0.142)	-1.865*** (0.667)	0.118 (0.250)
Avail. lending	-0.138*** (0.032)	-0.124*** (0.029)	-0.394** (0.173)	-0.087 (0.072)
Bond time-to-mat.	0.024 (0.019)	0.031* (0.017)	0.033 (0.053)	0.039 (0.027)
D. Auction	-4.519** (1.791)	-3.891 (2.359)	-9.228*** (2.567)	-3.311*** (0.643)
Bid-ask spread	-0.020* (0.010)	-0.021 (0.018)	-0.037** (0.015)	-0.020* (0.012)
CDS bond (log)	0.991*** (0.267)	0.439*** (0.115)	9.443** (4.380)	1.226*** (0.319)
Constant	-2.747*** (1.006)	-0.412 (0.514)	-49.388** (23.671)	-4.960*** (1.731)
R^2	0.785	0.799	0.744	0.662
Num. Obs.	37602	26987	4858	5757

Table 5: **Specialness and SMP purchases** - The table shows the results of OLS (Columns (1) – (2)) and quantile (Columns (3) – (4)) panel regressions with bond fixed effects. Specialness is expressed in basis points and is based on spot next (SN) and tomorrow next (TN) transactions. The repo imbalance is based on spot next (SN) and tomorrow next (TN) transactions. The repo imbalance, cash imbalance, available for lending and SMP purchase variables are rescaled by the nominal outstanding amount of the bond, expressed in percentage terms and are lagged by one day (see Section 3.1 for details). Bond time-to-maturity denotes the time-to-maturity of a specific security. Bid-ask spread denotes the bid-ask spread based on BGN Bloomberg prices at or before 5pm. D. Auction is a dummy variable to control for the date of a primary issuance of the security. The variable CDS bond is based on the term structure of US dollar-denominated Italian sovereign CDS contracts. Every day we interpolate the term structure of CDS spreads and match the implied CDS spread with the bond with same time-to-maturity. The CDS bond variable is expressed in logarithmic and lagged by one day. In Column (2) the observations on the 10–year on-the-run bonds are excluded from the sample. Standard errors are in parenthesis and are clustered by bond identifier (Columns (1) – (2))). The estimation is carried out for the sub-period 8 August 2011 - 21 December 2011. Stars denote statistical significance at 10% (*), 5% (**) and 1% (***)).

	(1)	(2)	(3)	(4)
	OLS	OLS	Q-70	Q-90
Specialness (lag)	0.796*** (0.093)	0.678*** (0.118)		
Repo imbalance	1.179** (0.526)	0.406 (0.295)	0.800*** (0.240)	3.916*** (0.712)
Cash imbalance	-2.010*** (0.726)	-1.633*** (0.612)	-2.100** (0.931)	-3.119 (2.759)
Avail. lending	-0.370** (0.171)	-0.387** (0.194)	-1.105*** (0.176)	-2.661*** (0.520)
Bond time-to-mat.	0.020 (0.049)	-0.026 (0.052)	0.014 (0.074)	0.682*** (0.220)
D. Auction	-8.861*** (2.548)	-7.408*** (2.499)	-9.063 (6.284)	-12.021 (18.619)
Bid-ask spread	-0.031** (0.015)	-0.041** (0.017)	-0.107 (0.086)	-0.211 (0.256)
CDS bond (log)	9.676** (4.351)	13.334** (5.220)	43.523*** (2.437)	46.947*** (7.221)
SMP purchase	4.660*** (0.822)	4.735*** (1.652)	6.559*** (1.334)	18.349*** (3.953)
Constant	-51.121** (23.522)	-70.298** (28.327)	-227.997*** (14.859)	-223.297*** (44.024)
R^2	0.745	0.739		
Num. Obs.	4858	4770	4858	4858

Table 6: **10-year on-the-run bonds: Cash premium, bond market liquidity and short-selling premium** - The table reports the results from predictive OLS regressions in which the dependent variable is: 1) the cash premium; 2) the bid-ask spread differential; 3) the short-selling premium. The cash premium and short-selling premium are calculated from a strategy composed of a duration-adjusted long position in the 10-year off-the-run bonds and a short position in the 10-year on-the-run bonds (see details in Section 5.2). The bid-ask spread differential is calculated as the difference between the bid-ask spread of the 10-year on-the-run and off-the-run bonds. The explanatory variables are: the difference between the daily specialness of on-the-run and off-the-run bonds, the difference between the SMP daily purchases of on-the-run and off-the-run bonds, the CDS bond spread of 10-year on-the-run bonds and a dummy variable for the primary issuance of the 10-year on-the-run bonds. Observations are daily and the regressors are lagged by one day. Estimation is carried out for the sub-period 8 August 2011 - 21 December 2011. Standard errors are in parenthesis and are clustered by bond identifier. Stars denote statistical significance at 10% (*), 5% (**) and 1% (***)).

	(1)	(2)	(3)
	Cash premium On - Off	Bid-ask spread On - Off	Short-selling premium On - Off
Specialness[On - Off]	0.0002** (0.000)	-0.0001 (0.0001)	0.0633** (0.025)
SMP purchase[On - Off]	0.0255*** (0.003)	0.0208*** (0.0038)	9.3568*** (0.416)
CDS Bond (log)	0.0980 (0.059)	-0.0099 (0.0421)	28.1207** (12.239)
D. Auction	-0.0938 (0.065)	-0.0953*** (0.0317)	-16.8061*** (1.598)
Constant	-0.6197* (0.357)	0.1170 (0.2361)	-1.7e+02** (73.750)
R^2	0.065	0.104	0.141
Num. Obs.	175	175	171

Table 7: **Fails-to-deliver** - The table shows the results of Probit and OLS panel regressions estimated with bond fixed effects. The dependent variable for the Probit estimation is equal to one when at least a fail-to-deliver occurs at time $t + 3$ (see Columns (1) – (3)). For this estimation we report the marginal effects of the regressors. In the OLS estimation the dependent variable corresponds to the nominal amount of settlement fails over the nominal amount traded at time $t + 3$ (see Columns (4) – (6)). In Column (2) and (5) the sample is restricted to the bonds purchased by the ECB under the SMP. Specialness and repo imbalance are based on spot next (SN) and tomorrow next (TN) transactions. The repo imbalance, cash imbalance, available for lending and SMP purchase variables are rescaled by the nominal outstanding amount of the bond, and expressed in percentage terms (see Section 3.1 for details). Bond time-to-maturity denotes the time-to-maturity of a specific security. Bid-ask spread denotes the bid-ask spread based on BGN Bloomberg prices at or before 5pm. D. Auction is a dummy variable to control for the date of a primary issuance of the security. The variable CDS bond is based on the term structure of US dollar-denominated Italian sovereign CDS contracts. Every day we interpolate the term structure of CDS spreads and match the implied CDS spread with the bond with same time-to-maturity. The CDS bond variable is expressed in logarithmic. Standard errors are in parenthesis and are clustered by bond identifier. Estimation is carried out for the sub-period 8 August 2011 - 21 December 2011. Stars denote statistical significance at 10% (*), 5% (**) and 1% (***) .

	(1)	(2)	(3)	(4)	(5)	(6)
	Probit	Probit	Probit	OLS	OLS	OLS
Specialness	0.0032*** (0.0004)	0.0025*** (0.0004)		0.055*** (0.008)	0.039*** (0.005)	
D. Penalties	-0.0533* (0.0319)	- 0.0551 (0.0467)	-0.0439 (0.0331)	0.806 (0.664)	0.339 (0.690)	0.782 (0.707)
SMP purchase			0.1461*** (0.0443)			0.574* (0.309)
Repo imbalance	0.0096* (0.0054)	0.0131* (0.0079)	0.0148*** (0.0054)	0.402*** (0.108)	0.660*** (0.158)	0.563*** (0.135)
Cash imbalance	0.0015 (0.0175)	0.0803 (0.0562)	-0.0064 (0.0207)	-1.008* (0.596)	0.420 (0.397)	-1.042 (0.650)
Avail. lending	-0.0076* (0.0045)	0.0105 (0.0148)	- 0.0128** (0.0053)	-0.094 (0.069)	-0.020 (0.153)	-0.204** (0.096)
Bond time-to-mat.	0.0071*** (0.0019)	0.0151* (0.0083)	0.0076*** (0.0022)	0.022 (0.029)	0.230** (0.113)	0.043 (0.038)
D. Auction	0.0605 (0.0734)	-0.0670 (0.1312)	0.0179 (0.0686)	-0.855 (0.716)	-0.624 (1.401)	-1.758** (0.857)
Bid-ask spread	-0.0044 (0.0042)	0.0022 (0.0291)	-0.0050 (0.0047)	0.023 (0.036)	0.682* (0.385)	0.011 (0.035)
CDS bond (log)	0.2003*** (0.0773)	0.1972 (0.1612)	0.3140*** (0.0851)	-2.378 (1.740)	1.089 (1.828)	-0.266 (1.792)
R^2				0.093	0.127	0.029
Num. Obs.	4890	2046	4890	4890	2046	4890

Table 8: **Specialness, SMP purchases and ECB collateral pledge** - The table shows the results of OLS (Columns (1)–(2)) and quantile (Columns (3)–(4)) panel regressions with bond fixed effects. Specialness is expressed in basis points and is based on spot next (SN) and tomorrow next (TN) transactions. The repo imbalance is based on spot next (SN) and tomorrow next (TN) transactions. The repo imbalance, cash imbalance, available for lending, SMP purchase and ECB collateral pledge variables are scaled by the nominal outstanding amount of the bond, expressed in percentage terms and are lagged by one day (see Section 3.1 for details). Bond time-to-maturity denotes the time-to-maturity of a specific security. Bid-ask spread denotes the bid-ask spread based on BGN Bloomberg prices at or before 5pm. D. Auction is a dummy variable to control for the date of a primary issuance of the security. The variable CDS bond is based on the term structure of US dollar-denominated Italian sovereign CDS contracts. Every day we interpolate the term structure of CDS spreads and match the implied CDS spread with the bond with same time-to-maturity. The CDS bond variable is expressed in logarithmic and lagged by one day. In Column (2) the observations on the 10–year on-the-run bonds are excluded from the sample. Standard errors are in parenthesis and are clustered by bond identifier (Columns (1) – (2))). Estimation is carried out for the sub-period 8 August 2011 - 21 December 2011. Stars denote statistical significance at 10% (*), 5% (**) and 1% (***)).

	(1)	(2)	(3)	(4)
	OLS	OLS	Q-70	Q-90
Specialness (lag)	0.793*** (0.094)	0.675*** (0.118)		
Repo imbalance	1.165** (0.524)	0.389 (0.292)	0.635*** (0.237)	3.845*** (0.770)
Cash imbalance	-2.033*** (0.727)	-1.662*** (0.624)	-2.337** (0.917)	-2.000 (2.980)
Avail. lending	-0.358** (0.168)	-0.378* (0.192)	-1.083*** (0.173)	-2.459*** (0.563)
Bond time-to-mat.	0.030 (0.048)	-0.013 (0.050)	0.049 (0.073)	0.653*** (0.238)
D. Auction	-9.067*** (2.562)	-7.595*** (2.516)	-8.758 (6.191)	-16.313 (20.112)
Bid-ask spread	-0.032* (0.016)	-0.042** (0.018)	-0.115 (0.085)	-0.233 (0.276)
CDS bond (log)	10.441** (4.708)	14.225** (5.585)	45.892*** (2.433)	51.723*** (7.902)
SMP purchase	4.459*** (0.803)	4.389*** (1.612)	5.522*** (1.320)	18.126*** (4.288)
ECB collateral pledge	-0.214 (0.136)	-0.242* (0.144)	-0.554*** (0.126)	-1.097*** (0.410)
Constant	-55.097** (25.367)	-74.912** (30.221)	-240.916*** (14.778)	-249.056*** (48.005)
R^2	0.746	0.616		
Num. Obs.	4858	4770	4858	4858

Appendix A. A dynamic search-based model with central bank

In this section we extend the search-based dynamic model by Vayanos and Weill (2008) (thereafter VW) using the same notation. To solve the model we proceed in two steps. First, both spot and repo markets operate through search mechanism where agents are matched randomly in pairs over time. We compute the population measures for each agent's type in Subsection A.1. Second, in equilibrium, the agents agree to trade whenever there are potential gains from trade. Price and lending fee (or specialness) are derived in Subsection A.2.

A.1. Population measures

This section describes the types of agents and the transition between types. The possible types are presented in Table B-I.

In VW model, at each point in time, there is a flow \bar{F} of average-valuation agents who switch to high valuation, and a flow \underline{F} of average-valuation agents who switch to low valuation. High-valuation agents revert to average valuation with Poisson intensity $\bar{\kappa}$, and low-valuation agents do the same with Poisson intensity $\underline{\kappa}$. We introduce the central bank as an average-valuation agent who switches to high valuation with its flow \bar{F}^{cb} and Poisson intensity $\bar{\kappa}^{cb}$. Thus, the steady-state measures of high-valuation agents are $\bar{F}/\bar{\kappa}$ and $\bar{F}^{cb}/\bar{\kappa}^{cb}$ respectively, while the steady-state measure of low-valuation agents are $\underline{F}/\underline{\kappa}$.

In equilibrium, high-valuation agents are the marginal asset holders. Indeed, the aggregate asset supply is the sum of the supply S from the issuers of the two assets plus the supply from the short-sellers. Since low-valuation agents are the only short-sellers and short one share, the latter supply is equal to their measure $\underline{F}/\underline{\kappa}$. The aggregate supply is thus smaller than the measure of high-valuation agents, asset demand, meaning that these agents are marginal:

$$\frac{\bar{F}}{\bar{\kappa}} + \frac{\bar{F}^{cb}}{\bar{\kappa}^{cb}} > 2S + \frac{\underline{F}}{\underline{\kappa}}. \quad (\text{A-1})$$

We modify the population measures to account for the central bank. μ_{bi} and μ_{si} denote the measures of buyers and sellers of asset i

$$\mu_{bi} = \mu_{\bar{b}} + \mu_{\bar{b}}^{cb} + \mu_{bi} \quad (\text{A-2})$$

$$\mu_{si} = \mu_{\bar{s}i} + \mu_{\bar{s}i}^{cb} + \mu_{\underline{s}i} \quad (\text{A-3})$$

where $\mu_{\bar{b}}^{cb}$ and $\mu_{\bar{s}i}^{cb}$ denote the measures of the central bank as a buyer of all assets and as a

seller of asset i respectively. Since assets are held by either central bank, lenders or sellers, market clearing implies

$$\mu_{\bar{i}} + \mu_{\bar{h}i}^{cb} + \mu_{si} = S \quad (\text{A-4})$$

where $\mu_{\bar{i}}$ denotes the measure of asset i held by the high-valuation agent who bought the asset i and seeks to lend it and $\mu_{\bar{h}i}^{cb}$ denotes the measure of asset i held by the high-valuation central bank who keeps the asset in its portfolio.

In VW model the inflow-outflow equations for the high-valuation agents are as follows

$$\text{Buyers} \quad \bar{F} = \bar{\kappa}\mu_{\bar{b}} + \sum_{i=1}^2 \lambda\mu_{si}\mu_{\bar{b}} \quad (\text{A-5})$$

$$\text{Lenders} \quad \lambda\mu_{si}\mu_{\bar{b}} + f_i = \bar{\kappa}\mu_{\bar{i}} + \nu_i\mu_{\underline{b}o}\mu_{\bar{i}} \quad (\text{A-6})$$

$$\text{Non-searchers} \quad \nu_i\mu_{\underline{b}o}\mu_{\bar{i}} = f_i + \bar{\kappa}\mu_{\bar{n}i} \quad (\text{A-7})$$

$$\text{Sellers} \quad \bar{\kappa}\mu_{\bar{i}} + \bar{\kappa}\mu_{\bar{s}i} = \lambda\mu_{bi}\mu_{\bar{s}i}. \quad (\text{A-8})$$

For example in Equation (A-5), the left-hand side is the inflow of \bar{F} of high-valuation agents. The right-hand side is the outflow. Some agents switch to average valuation and become sellers $\bar{\kappa}\mu_{\bar{b}}$ and some agents meet sellers and become buyers $\lambda\mu_{si}\mu_{\bar{b}}$ of asset i where λ is the parameter measuring the efficiency of the spot-market search. Thus, meetings of buyers and sellers of asset i occur at a deterministic rate $\lambda\mu_{si}\mu_{\bar{b}}$. The Appendix of the working paper Vayanos and Weill (2005) provides a description of each equation.

We introduce the inflow-outflow equations for the high-valuation central bank as follows

$$\text{Central bank buyer} \quad \bar{F}^{cb} = \bar{\kappa}^{cb}\mu_{\bar{b}}^{cb} + \sum_{i=1}^2 \lambda\mu_{si}\mu_{\bar{b}}^{cb} \quad (\text{A-9})$$

$$\text{Central bank holder} \quad \lambda\mu_{si}\mu_{\bar{b}}^{cb} = \bar{\kappa}^{cb}\mu_{\bar{h}i} \quad (\text{A-10})$$

$$\text{Central bank seller} \quad \bar{\kappa}^{cb}\mu_{\bar{h}i} = \lambda\mu_{bi}\mu_{\bar{s}i}^{cb}. \quad (\text{A-11})$$

Two key parameters distinguish Equation (A-9) from Equation (A-5). The \bar{F}^{cb} flow of the central bank proxies for the intensity of the purchases and the central bank as high-valuation agent switches to average valuation with a lower probability $\bar{\kappa}^{cb}$ proxying for the hold-to-maturity portfolio strategy. In Equation (A-10) the inflow is $\lambda\mu_{si}\mu_{\bar{b}}^{cb}$ because the central bank meets sellers of asset i and becomes buyer. The outflow is $\bar{\kappa}^{cb}\mu_{\bar{h}i}$ because the central bank reverts to average valuation. After buying the asset i , the central bank does not lend the asset i to short-sellers. In Equation (A-11) the inflow is $\bar{\kappa}^{cb}\mu_{\bar{h}i}$ because the central bank reverts to average valuation and corresponds to the outflow of Equation (A-10). The

outflow is $\lambda\mu_{bi}\mu_{\bar{si}}^{cb}$ because the central bank as a seller meets a buyer of asset i and exits the market.

In VW model the inflow-outflow equations for the low-valuation agents are as follows

$$\text{Borrowers} \quad \underline{F} + \sum_{i=1}^2 \bar{\kappa}(\mu_{\underline{si}} + \mu_{\underline{ni}}) = \underline{\kappa}\mu_{\underline{bo}} + \sum_{i=1}^2 \nu_i\mu_{\underline{bo}}\mu_{\bar{i}} \quad (\text{A-12})$$

$$\text{Sellers} \quad \nu_i\mu_{\underline{bo}}\mu_{\bar{i}} = \bar{\kappa}\mu_{\underline{si}} + \underline{\kappa}\mu_{\underline{si}} + \lambda\mu_{bi}\mu_{\underline{si}} \quad (\text{A-13})$$

$$\text{Non-searchers} \quad \lambda\mu_{bi}\mu_{\underline{si}} = \bar{\kappa}\mu_{\underline{ni}} + \underline{\kappa}\mu_{\underline{ni}} \quad (\text{A-14})$$

$$\text{Buyers} \quad \underline{\kappa}\mu_{\underline{ni}} = \bar{\kappa}\mu_{\bar{bi}} + \lambda\mu_{\bar{bi}}\mu_{\underline{si}}. \quad (\text{A-15})$$

The total number of equations is 23 (because some are for each asset) from Equation (A–5) to (A–15). The 23 unknowns are the measures of types \bar{b} , \bar{b}^{cb} , \underline{bo} , $\{\bar{l}_i, \bar{n}_i, \bar{h}^{cb}_i, \bar{s}_i, \bar{s}^{cb}_i, \underline{s}_i, \underline{n}_i, \underline{b}_i\}_{i \in \{1,2\}}$ and $\{\mu_{bi}, \mu_{si}\}_{i \in \{1,2\}}$. We follow VW approach and we simplify the solutions for the measure equations. Thus, we solve numerically a reduced system of equations. See the Online Appendix for the derivation of the reduced system.

A.2. Prices and lending fees

In VW model the value equations for the high-valuation agent are as follows

$$\text{Buyers} \quad rV_{\bar{b}} = -\bar{\kappa}V_{\bar{b}} + \sum_{i=1}^2 \lambda\mu_{si}(V_{\bar{i}} - p_i - V_{\bar{b}}) \quad (\text{A-16})$$

$$\text{Lenders} \quad rV_{\bar{i}} = \delta + \bar{x} - y + \bar{\kappa}(V_{\bar{si}} - V_{\bar{i}}) + \nu_i\mu_{\underline{bo}}(V_{\bar{n}si} - V_{\bar{i}}) \quad (\text{A-17})$$

$$\text{Non-searchers \&} \quad rV_{\bar{n}si} = \delta + \bar{x} - y + \omega_i + \bar{\kappa}(V_{\bar{si}} - V_{\bar{n}si}) +$$

$$\text{Sellers} \quad \underline{\kappa}(V_{\bar{i}} - V_{\bar{n}si}) + \lambda\mu_{bi}(V_{\bar{n}ni} - V_{\bar{n}si}) \quad (\text{A-18})$$

$$\text{Non-searchers \&} \quad rV_{\bar{n}ni} = \delta + \bar{x} - y + \omega_i + \bar{\kappa}(C_i - V_{\bar{n}ni}) +$$

$$\text{Non-searchers} \quad \underline{\kappa}(V_{\bar{b}i} - V_{\bar{n}ni}) \quad (\text{A-19})$$

$$\text{Non-searchers \&} \quad rV_{\bar{b}i} = \delta + \bar{x} - y + \omega_i + \bar{\kappa}(C_i - V_{\bar{b}i}) +$$

$$\text{Buyers} \quad \lambda\mu_{si}(V_{\bar{i}} - V_{\bar{b}i}) \quad (\text{A-20})$$

$$\text{Sellers} \quad rV_{\bar{si}} = \delta - y + \lambda\mu_{bi}(p_i - V_{\bar{si}}), \quad (\text{A-21})$$

where δ represents the dividend flow, y represents the cost of bearing risk, the parameters \bar{x} and \underline{x} represent the hedging benefits. p_i and ω_i represent the asset price and the lending fee (or specialness) of asset i respectively, while C_i denotes the cash collateral seized by the lender when the borrower cannot deliver it instantly. For example in Equation (A-17)

for the lender, $\delta + \bar{x} - y$ is the certainty equivalent of holding one share derived from the CARA specification (see Appendix in Vayanos and Weill (2008)). The term $\bar{\kappa}(V_{\bar{s}i} - V_{\bar{l}i})$ is the transition to average valuation at rate $\bar{\kappa}$ and to become a seller \bar{s} . The term $\nu_i \mu_{b\bar{o}}(V_{\bar{n}si} - V_{\bar{l}i})$ is the transition of meeting a borrower at rate $\nu_i \mu_{b\bar{o}}$, lending the asset i , and becoming a non-searcher type associated with a short-seller, $\bar{n}si$. The parameter ν_i is the parameter measuring the efficiency of the repo-market search for asset i . The Appendix of the working paper Vayanos and Weill (2005) provides a description of each equation.

For the high-valuation central bank agent we have

$$\text{Central bank buyer} \quad rV_{\bar{b}}^{cb} = -\bar{\kappa}^{cb}V_{\bar{b}}^{cb} + \sum_{i=1}^2 \lambda\mu_{si}(V_{\bar{h}i}^{cb} - p_i - V_{\bar{b}}^{cb}) \quad (\text{A-22})$$

$$\text{Central bank holder} \quad rV_{\bar{h}i}^{cb} = \delta + \bar{x} - y + \bar{\kappa}^{cb}(V_{\bar{s}i}^{cb} - V_{\bar{h}i}^{cb}) \quad (\text{A-23})$$

$$\text{Central bank seller} \quad rV_{\bar{s}i}^{cb} = \delta - y + \lambda\mu_{bi}(p_i - V_{\bar{s}i}^{cb}). \quad (\text{A-24})$$

In Equation (A-22) the central bank seeks to buy the asset and it might revert to average valuation exiting the market at rate $\bar{\kappa}^{cb}$. Eventually, it might meet a seller and buys asset i becoming a holder of the same asset, $\lambda\mu_{si}(V_{\bar{h}i}^{cb} - p_i - V_{\bar{b}}^{cb})$. In Equation (A-23) the central bank receives the flow benefit $\delta + \bar{x} - y$. The term $\bar{\kappa}^{cb}(V_{\bar{s}i}^{cb} - V_{\bar{h}i}^{cb})$ is the transition to average valuation at rate $\bar{\kappa}^{cb}$ and to become a seller \bar{s}^{cb} . In Equation (A-24) the flow benefit is $\delta - y$ of holding one share. The only transition is to meet a buyer at rate $\lambda\mu_{bi}$, sell at price p_i , and exit the market.

As in VW model, the value functions of the low-valuation agents are

$$\text{Borrowers} \quad rV_{\underline{b}\bar{o}} = -\underline{\kappa}V_{\underline{b}\bar{o}} + \sum_{i=1}^2 \nu_i \mu_{\bar{l}i}(V_{\underline{s}i} - V_{\underline{b}\bar{o}}) \quad (\text{A-25})$$

$$\begin{aligned} \text{Sellers} \quad rV_{\underline{s}i} &= -\omega_i + \bar{\kappa}(V_{\underline{b}\bar{o}} - V_{\underline{s}i}) + \\ &\quad - \underline{\kappa}V_{\underline{s}i} + \lambda\mu_{bi}(V_{\underline{n}i} + p_i - V_{\underline{s}i}) \end{aligned} \quad (\text{A-26})$$

$$\text{Non-searchers} \quad rV_{\underline{n}i} = -\delta + \underline{x} - y - \omega_i + \bar{\kappa}(V_{\underline{b}\bar{o}} - C_i - V_{\underline{n}i}) + \underline{\kappa}(V_{\underline{b}i} - V_{\underline{n}i}) \quad (\text{A-27})$$

$$\text{Buyers} \quad rV_{\underline{b}i} = -\delta - y - \omega_i + \bar{\kappa}(-C_i - V_{\underline{b}i}) + \lambda\mu_{si}(-p_i - V_{\underline{b}i}) \quad (\text{A-28})$$

Given short-selling decisions, ν_i , and types' measures, the linear system of Equations (A-16)-(A-28) determines uniquely the lending fees $\{\omega_i\}_{i \in 1,2}$ and prices $\{p\}_{i \in 1,2}$. We follow Section C of Vayanos and Weill (2005) to reduce the system of Equations (A-16)-(A-28) and we solve numerically the reduced system with Mathematica.

Appendix B. Computation of the cash and short-selling premium

In this section, we derive and compute the cash premium decomposition proposed by Banerjee and Graveline (2013). Consider two identical bonds, i and j , with respective price P_i and P_j that differ only by their liquidity, and therefore, by their shorting capability. Let Δ be the share of the liquid bond i that is sold short and let R be the premium to be paid to borrow that same security in the repo market (specialness).

The cash premium, C , can thus be decomposed in three components:

$$C = P_i - P_j = \underbrace{(1 + \Delta) \times C}_{\substack{\text{(1) Liquidity premium} \\ \text{paid by buyers} \\ \text{of the bond}}} - \underbrace{\Delta \times R}_{\substack{\text{(2) Financing premium} \\ \text{earned by buyers} \\ \text{of the bond}}} + \underbrace{\Delta \times (R - C)}_{\substack{\text{(3) Short-sellers pay} \\ \text{the financing premium} \\ \text{but sell at higher price}}}, \quad (\text{B-1})$$

where Δ is the fraction of the outstanding supply of the bond that it is sold short.

The decomposition in Equation (B-1) emphasizes the importance of jointly analyzing the cash premium, the borrowing or financing premium, and the fraction of the outstanding supply of the liquid security that it is sold short. A financing premium (i.e., $R > 0$) does not necessarily imply that short-sellers end up paying an overall net premium for positions in the liquid security, since it is possible that they recover completely these higher borrowing costs (i.e., if $C = R$). Similarly, a positive cash premium (i.e., $C > 0$) does not imply that long investors pay a net premium since they may be able to fully recover these costs by lending out their positions.⁵² Banerjee and Graveline (2013) show that short-sellers pay a liquidity premium (i.e., $R - C > 0$) when there are very long-term investors (hold-to-maturity investors), like central banks, that forgo the special premia they can earn by lending out their bonds and recover almost none of the price premium they pay for taking long positions in on-the-run bonds.

To calculate the borrowing premium, we compute the ex-post cost of short-selling an Italian bond, taking into account that the cash market for Italian sovereign bonds is typically two days settlement. If a trader short-sells an Italian on-the-run sovereign bond i at time t , he/she receives the sale price $P_{i,t}$ at time $t + 2$ and must borrow and deliver to the buyer the security on that date. To borrow the security at time $t + 2$, the short-seller enters a

⁵²Duffie (1996) and Krishnamurthy (2002) assume that there is an unconstrained arbitrageur who can hold arbitrarily large positions in the liquid security and lend out his entire position to short-sellers (while hedging the risk with an offsetting position in the illiquid security). This assumption ensures that short-sellers do not pay a liquidity premium (i.e., $R = C$), since otherwise the unconstrained long investor could make arbitrarily large profits by lending out all of his long positions in the liquid security at a premium and hedging with the illiquid security.

spot-next reverse repo transaction at time t , where the spot sale and forward repurchase prices are transacted simultaneously. He/she lends the spot sale price of the security $P_{i,t}^s$ to an owner of that security and receives the security as collateral at time $t + 2$. The interest rate $r_{i,t}^{sn}$ on the loan is referred to as the special repo rate for security i from $t + 2$ to $t + 3$, the spot-next rate. Then, the short-seller repurchases the bond and at time $t + 3$ he/she receives the Italian sovereign bond in exchange for the purchase price. He/she returns the Italian sovereign bond at the price $P_{i,t}^{s'}$ to the owner that he/she originally borrowed it from and receives $1 + r_{i,t}^{sn}$ for every euro that he/she has lent against the security. We assume that the difference, $P_{i,t+3} - P_{i,t}^{s'}$ which may be either positive or negative, is financed at the general collateral repo rate r^{gc} (the highest available interest rate for lending against Italian collateral). Thus, the cost of short-selling 1 euro of the 10-year on-the-run Italian sovereign bond is

$$\text{Short-selling cost}_{i,t} = \frac{P_{i,t}^s - P_{i,t}^{s'}(1 + r_{i,t}^{sn}) + (P_{i,t+3} - P_{i,t}^{s'})(1 + r_{t+3}^{gc})}{P_{i,t}}. \quad (\text{B-2})$$

To isolate the price and borrowing premium, we compare the raw short-selling cost in Equation (B-2), to the cost of a short position with similar interest rate exposure in the off-the-run bond j . That is, we compare the cost of short-selling 1 euro of the on-the-run with the cost of short-selling $\text{DUR}_{i,t}/\text{DUR}_{j,t}$ euro in the off-the-run, where $\text{DUR}_{i,t}$ and $\text{DUR}_{j,t}$ are the duration of the on-the-run and off-the-run securities respectively.

The (liquidity) premium $R - C$ paid by short-sellers is then just the difference between the cost of short-selling the on-the-run bond and the cost of selling the duration adjusted position in the off-the-run which can be written as

$$(R - C)_{ij,t} = \text{Short-selling cost}_{i,t} - \frac{\text{DUR}_{i,t}}{\text{DUR}_{j,t}} \text{Short-selling cost}_{j,t}. \quad (\text{B-3})$$

The cash premium $C_{ij,t}$ is defined as

$$C_{ij,t} = \frac{\text{DUR}_{i,t}}{\text{DUR}_{j,t}} \left(\frac{P_{j,t+3}}{P_{j,t}} - 1 \right) - \left(\frac{P_{i,t+3}}{P_{i,t}} - 1 \right). \quad (\text{B-4})$$

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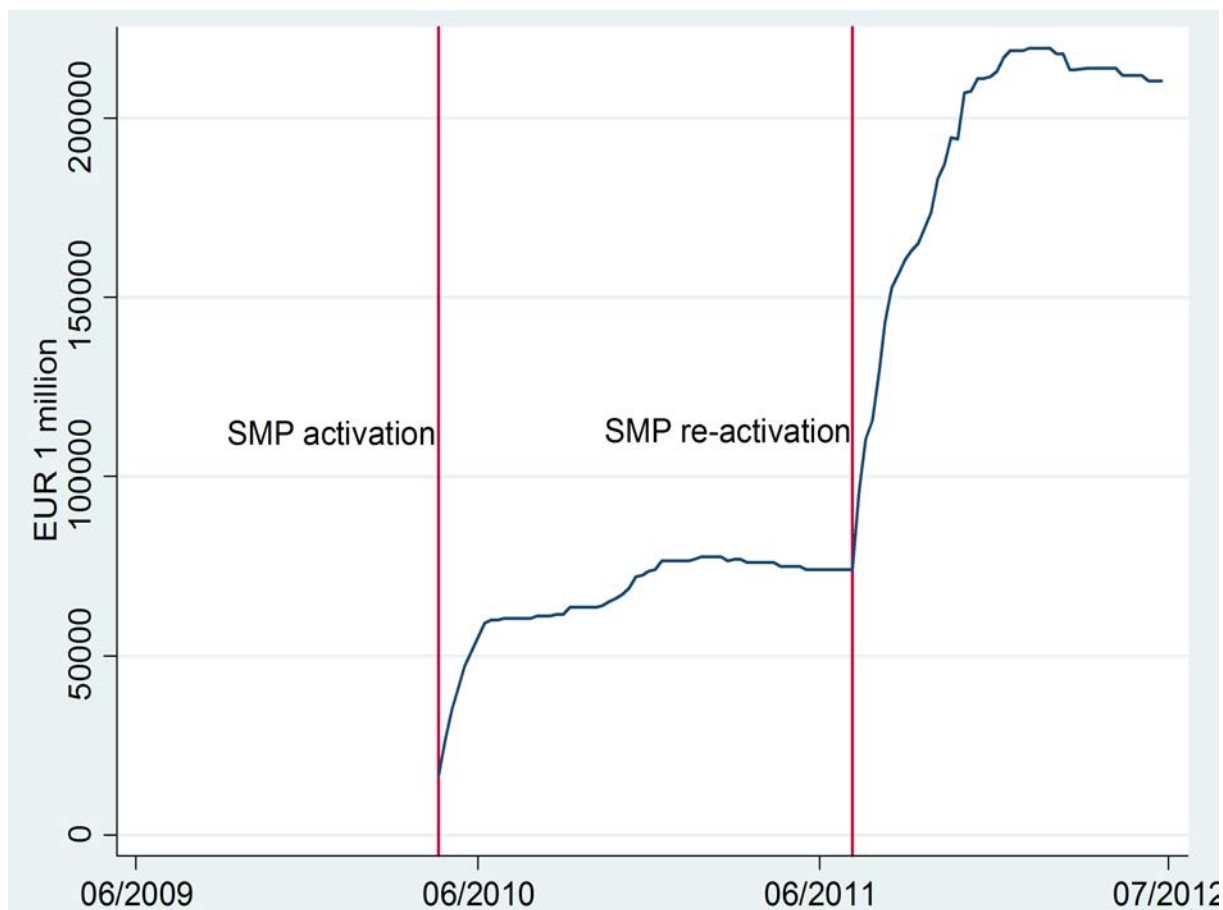


Fig. A-I. **The value of the Security Market Program (SMP) portfolio** - The figure plots the book value of the overall SMP portfolio held by the ECB. The value of the portfolio is at amortized cost in EUR millions as published by the ECB. The vertical lines indicate the dates at which the SMP was first activated (decision of the ECB Governing Council on 10 May 2010) and then reactivated (8 August 2011).

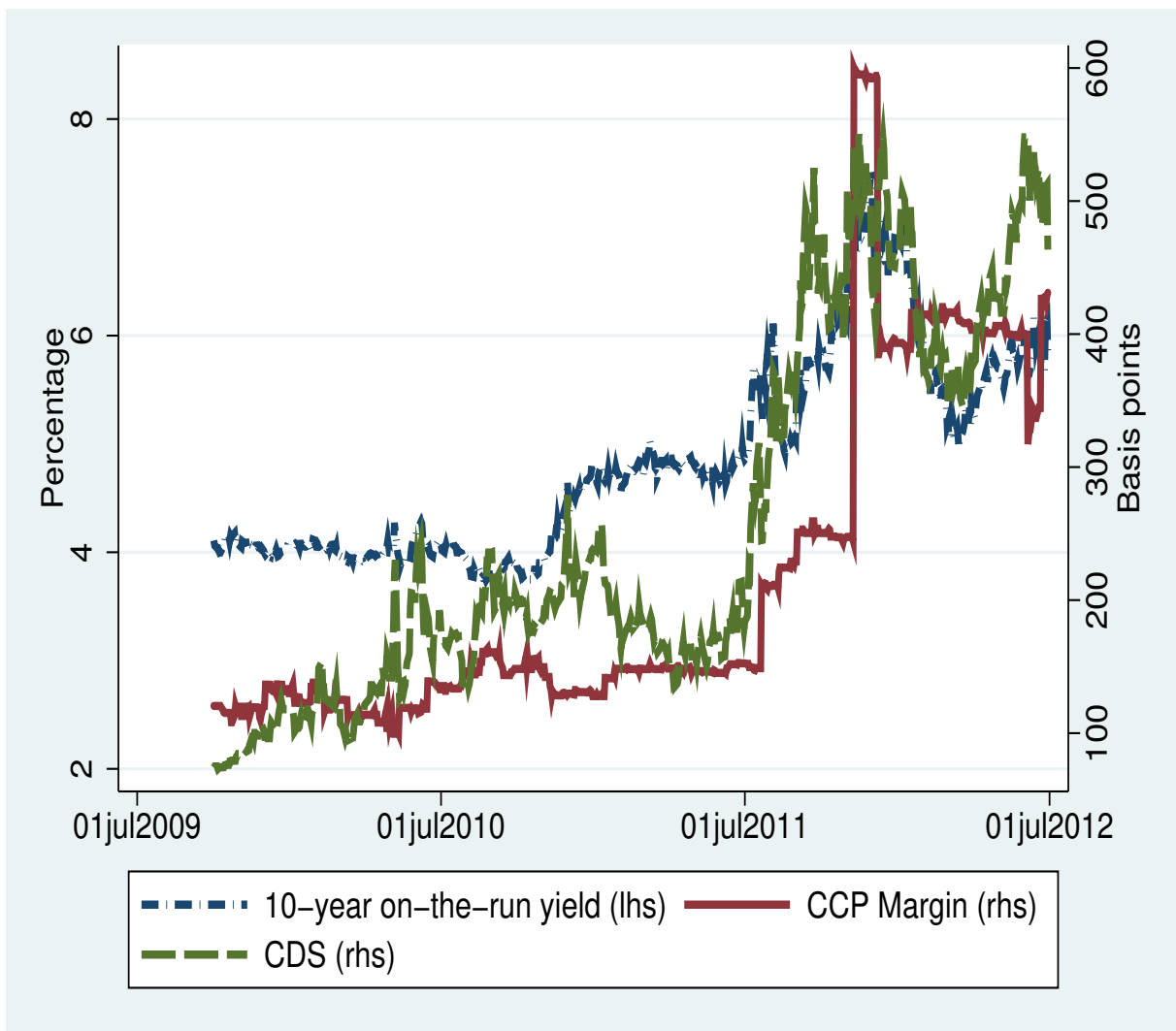


Fig. A-II. **Yields, CDS and CCP margins - 10-year on-the-run Italian sovereign bonds** - This figure plots the yield, CDS spread and CCP margin for the on-the-run Italian sovereign bonds with 10 years of maturity.

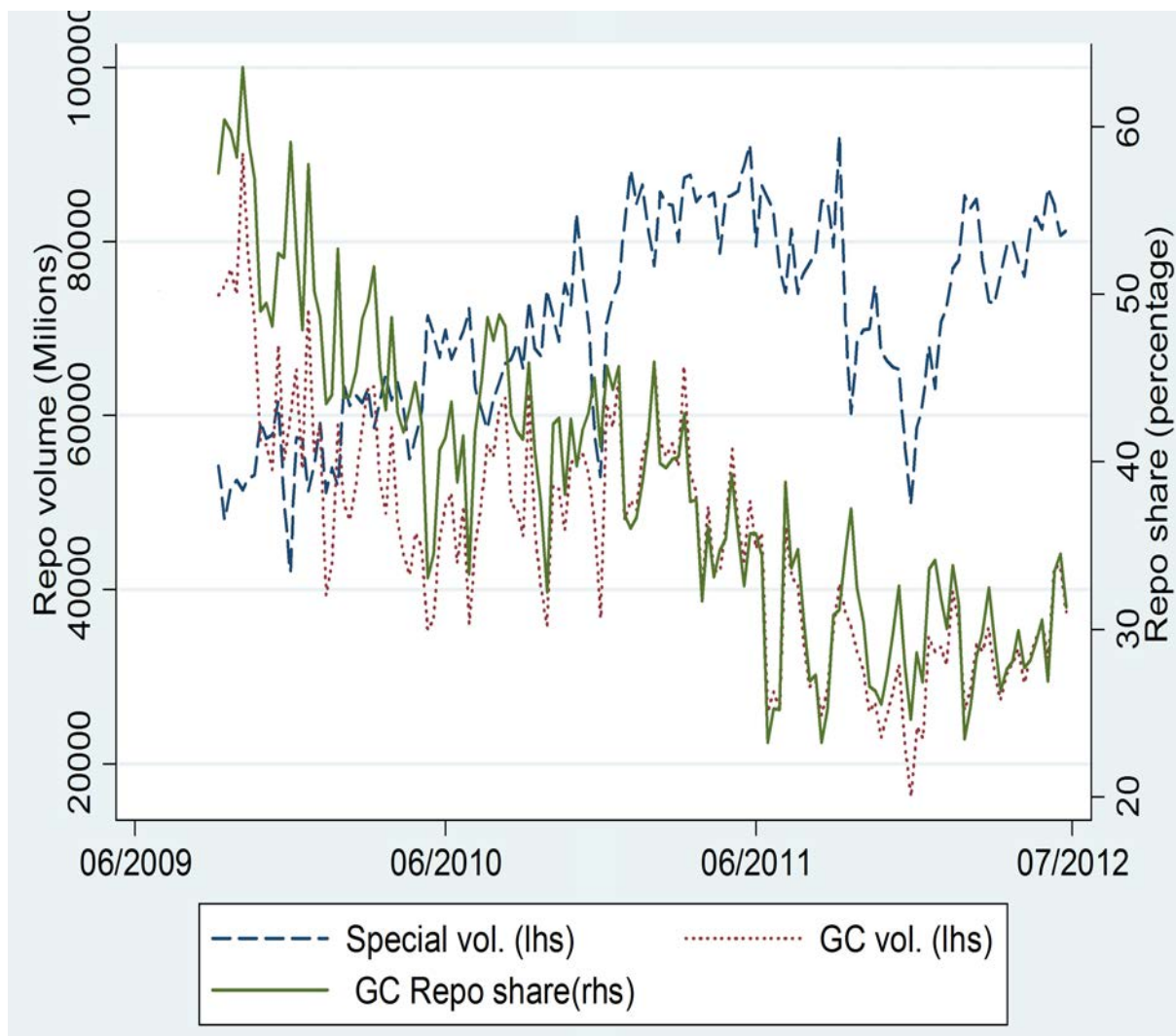


Fig. A-III. **Volume of general collateral (GC) and Special repos** - The figure plots the weekly volume of the general collateral (GC) and the Special repo transactions (left-hand scale, in EUR millions) and the share of GC repos over total repos (right-hand scale). The volumes refer to repo transactions with underlying Italian sovereign securities as traded on the MTS repo platform from 1 October 2009 to 7 July 2012.

Panel A - CDS bond

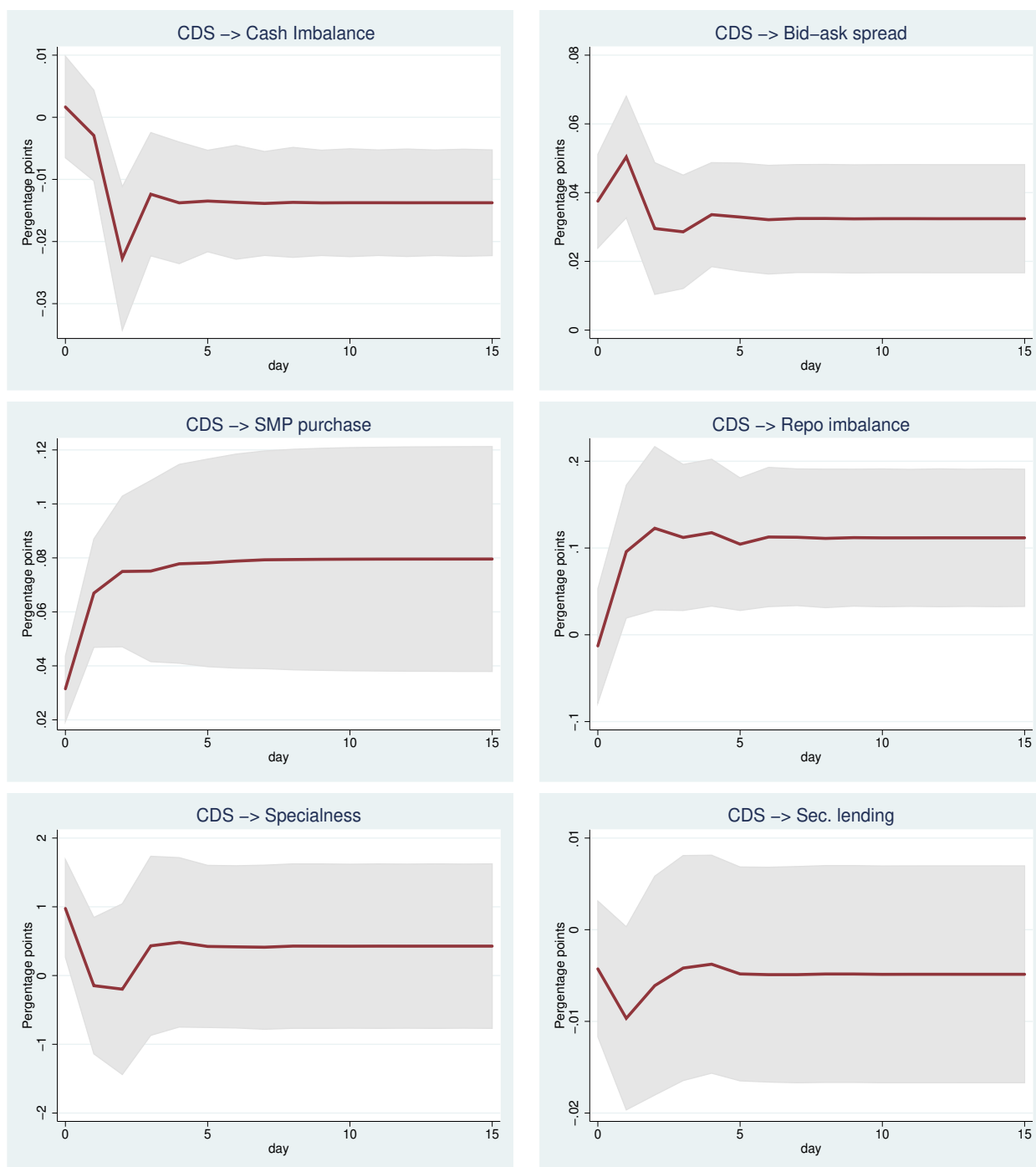


Fig. A-IV. **Panel VAR Cumulative IRFs - CDS bond** The figure plots the cumulative impulse response functions to a CDS bond shock of 1% and 90% bootstrapped confidence intervals (grey dashed lines) based on 1,000 replications. The cumulative impulse response functions are estimated from a panel VAR model in first-difference including the following variables: CDS bond, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending of the bonds purchased under the SMP from 8 August 2011 to 21 December 2011.

Panel B - Cash imbalance

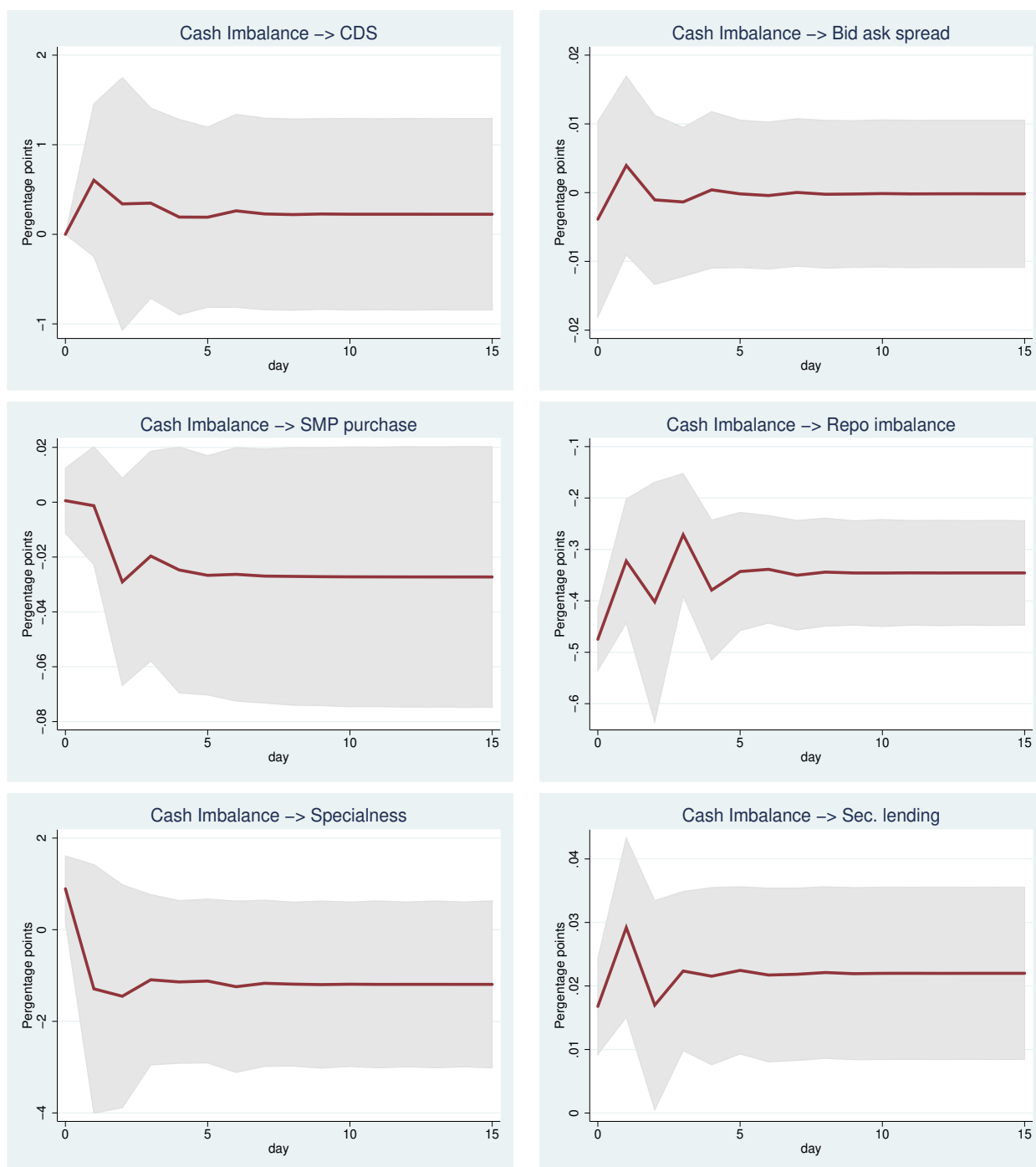


Fig. A-V. **Panel VAR Cumulative IRFs - Cash imbalance** The figure plots the cumulative impulse response functions to a cash imbalance shock of 1% and 90% bootstrapped confidence intervals (grey dashed lines) based on 1,000 replications. The cumulative impulse response functions are estimated from a panel VAR model in first-difference including the following variables: CDS bond, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending of the bonds purchased under the SMP from 8 August 2011 to 21 December 2011.

Panel C - Bid-ask spread

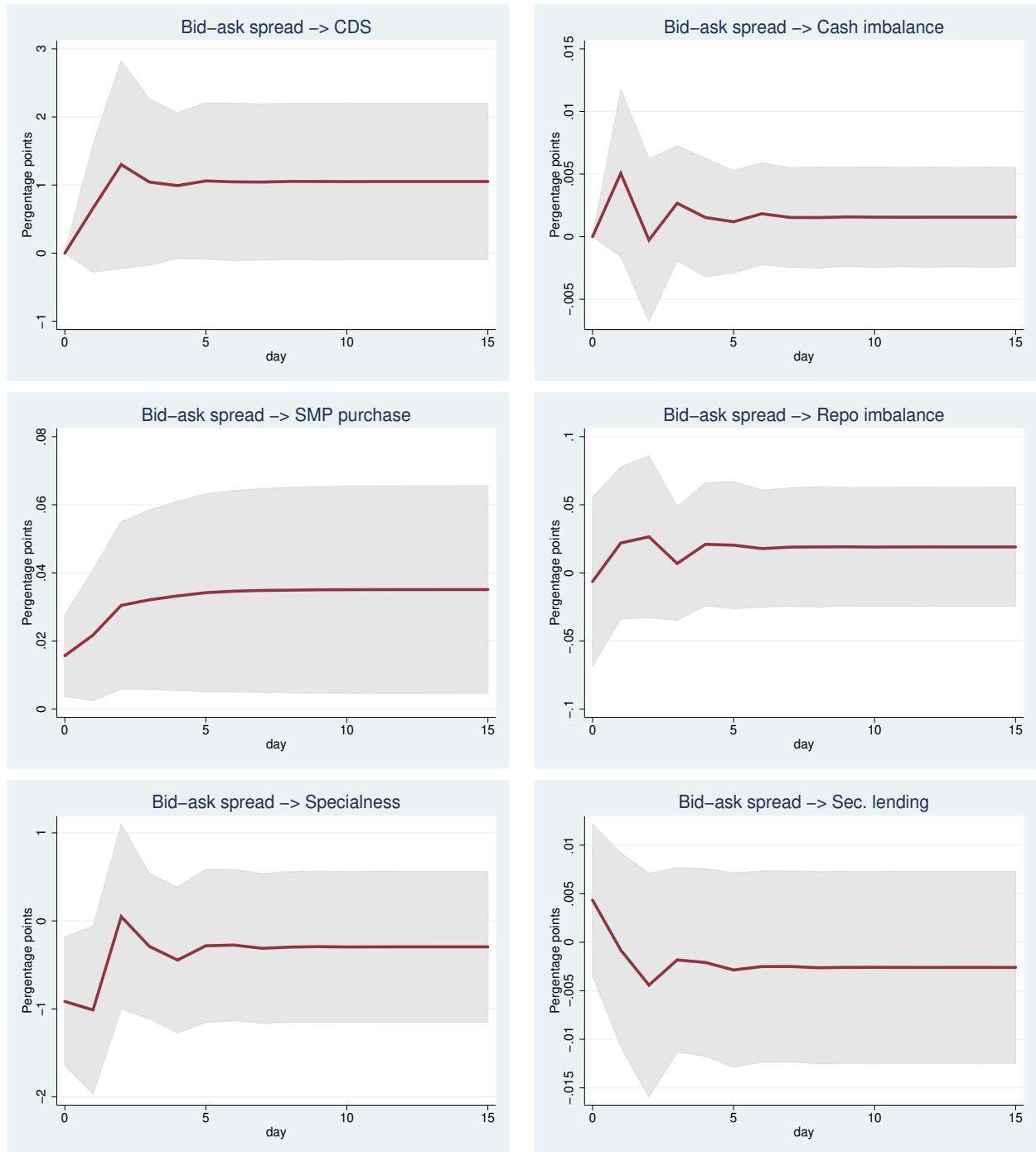


Fig. A-VI. **Panel VAR Cumulative IRFs - Bid-ask spread** The figure plots the cumulative impulse response functions to a bid-ask spread shock of 1% and 90% bootstrapped confidence intervals (grey dashed lines) based on 1,000 replications. The cumulative impulse response functions are estimated from a panel VAR model in first-difference including the following variables: CDS bond, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending of the bonds purchased under the SMP from 8 August 2011 to 21 December 2011.

Panel D - SMP purchase

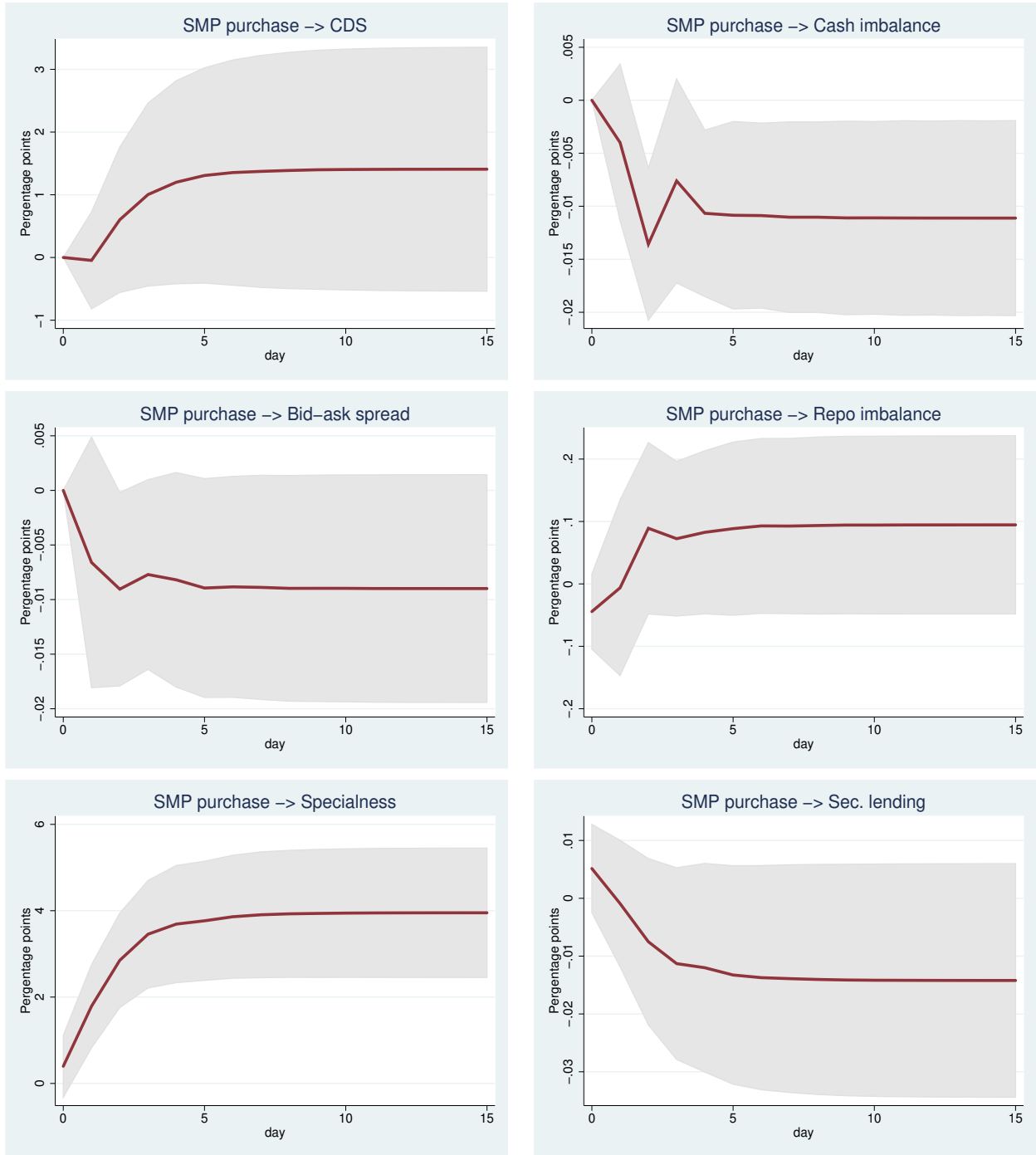


Fig. A-VII. **Panel VAR Cumulative IRFs - SMP purchase** The figure plots the cumulative impulse response functions to a SMP purchase shock of 1% and 90% bootstrapped confidence intervals (grey dashed lines) based on 1,000 replications. The cumulative impulse response functions are estimated from a panel VAR model in first-difference including the following variables: CDS bond, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending of the bonds purchased under the SMP from 8 August 2011 to 21 December 2011.

Panel E - Repo imbalance

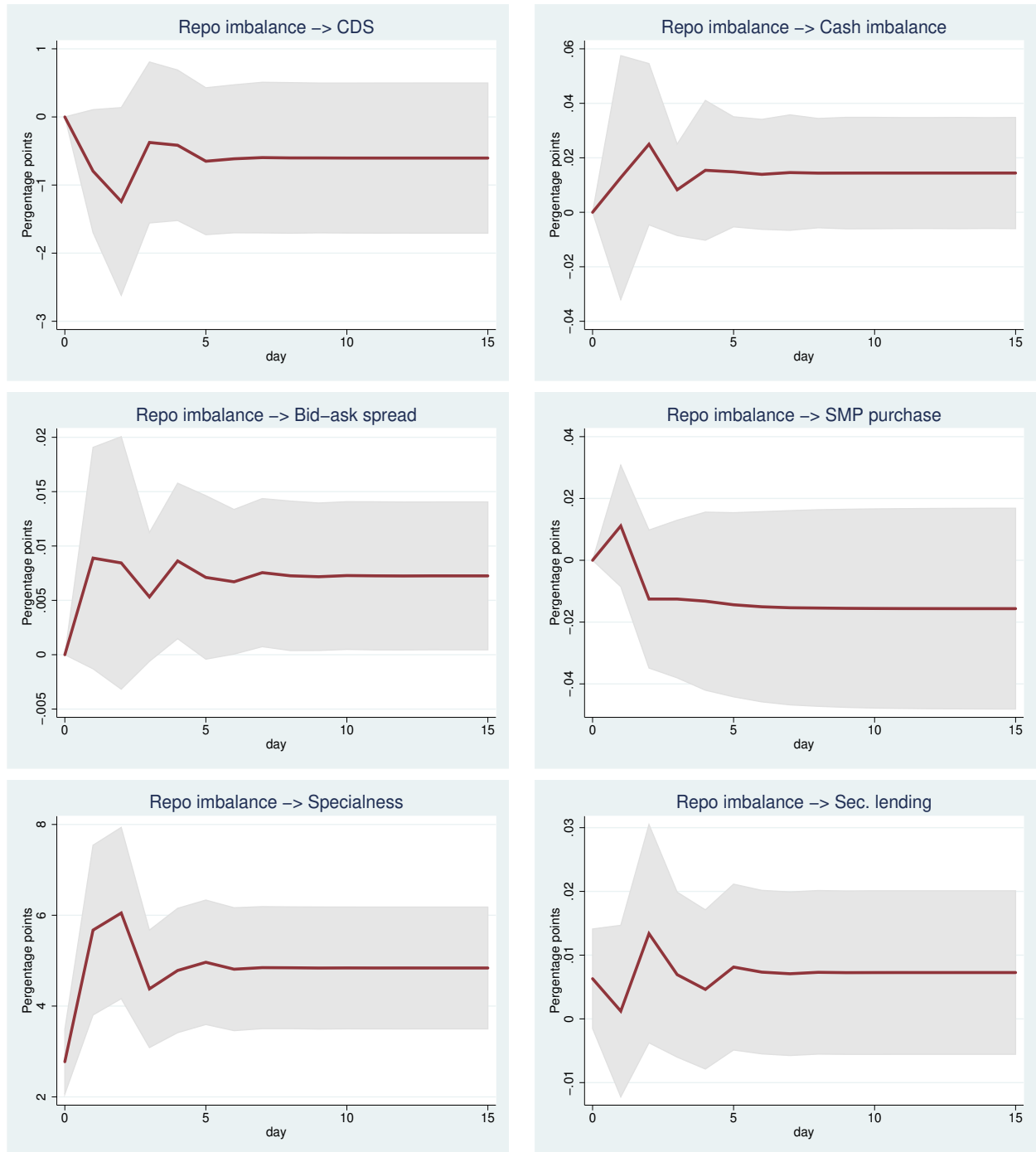


Fig. A-VIII. **Panel VAR Cumulative IRFs - Repo imbalance** The figure plots the cumulative impulse response functions to a repo imbalance shock of 1% and 90% bootstrapped confidence intervals (grey dashed lines) based on 1,000 replications. The cumulative impulse response functions are estimated from a panel VAR model in first-difference including the following variables: CDS bond, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending of the bonds purchased under the SMP from 8 August 2011 to 21 December 2011.

Panel F - Specialness

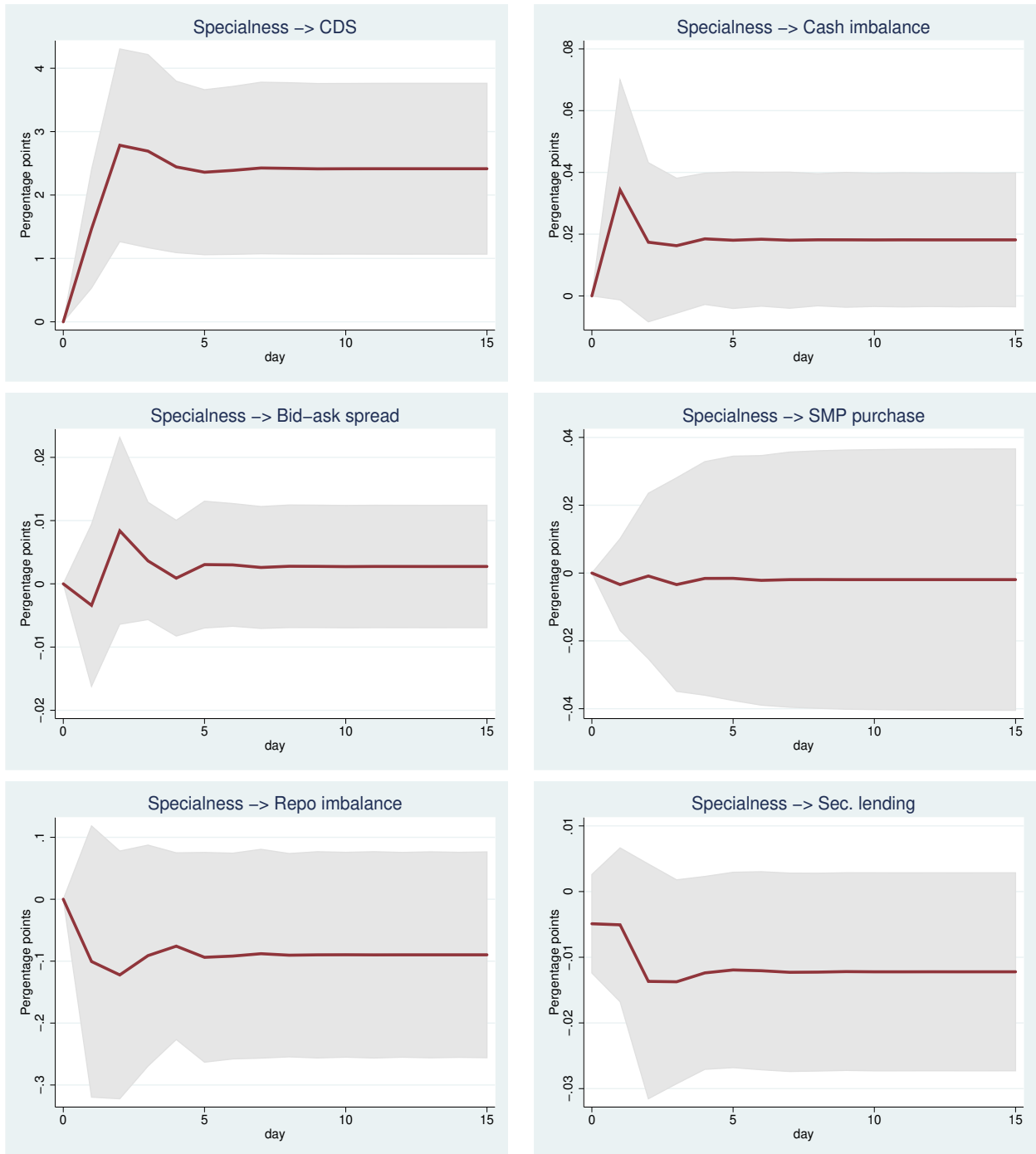


Fig. A-IX. **Panel VAR Cumulative IRFs - Specialness** The figure plots the cumulative impulse response functions to a specialness shock of 1% and 90% bootstrapped confidence intervals (grey dashed lines) based on 1,000 replications. The cumulative impulse response functions are estimated from a panel VAR model in first-difference including the following variables: CDS bond, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending of the bonds purchased under the SMP from 8 August 2011 to 21 December 2011.

Panel G - Available lending

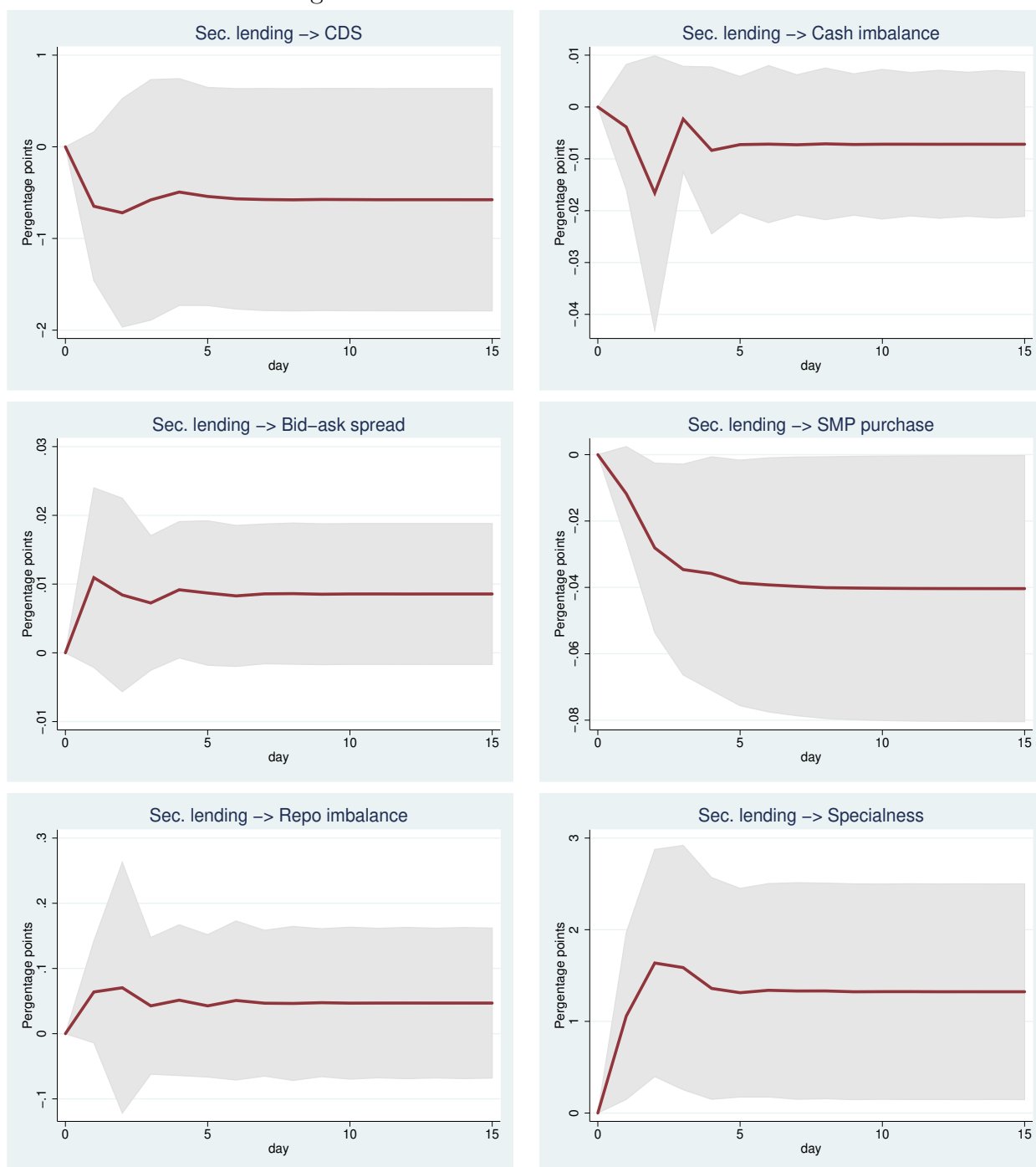


Fig. A-X. **Panel VAR Cumulative IRFs - Available lending** The figure plots the cumulative impulse response functions to a available for lending shock of 1% and 90% bootstrapped confidence intervals (grey dashed lines) based on 1,000 replications. The cumulative impulse response functions are estimated from a panel VAR model in first-difference including the following variables: CDS bond, cash imbalance, bid-ask spread, SMP purchase, repo imbalance, specialness and available for lending of the bonds purchased under the SMP from 8 August 2011 to 21 December 2011.

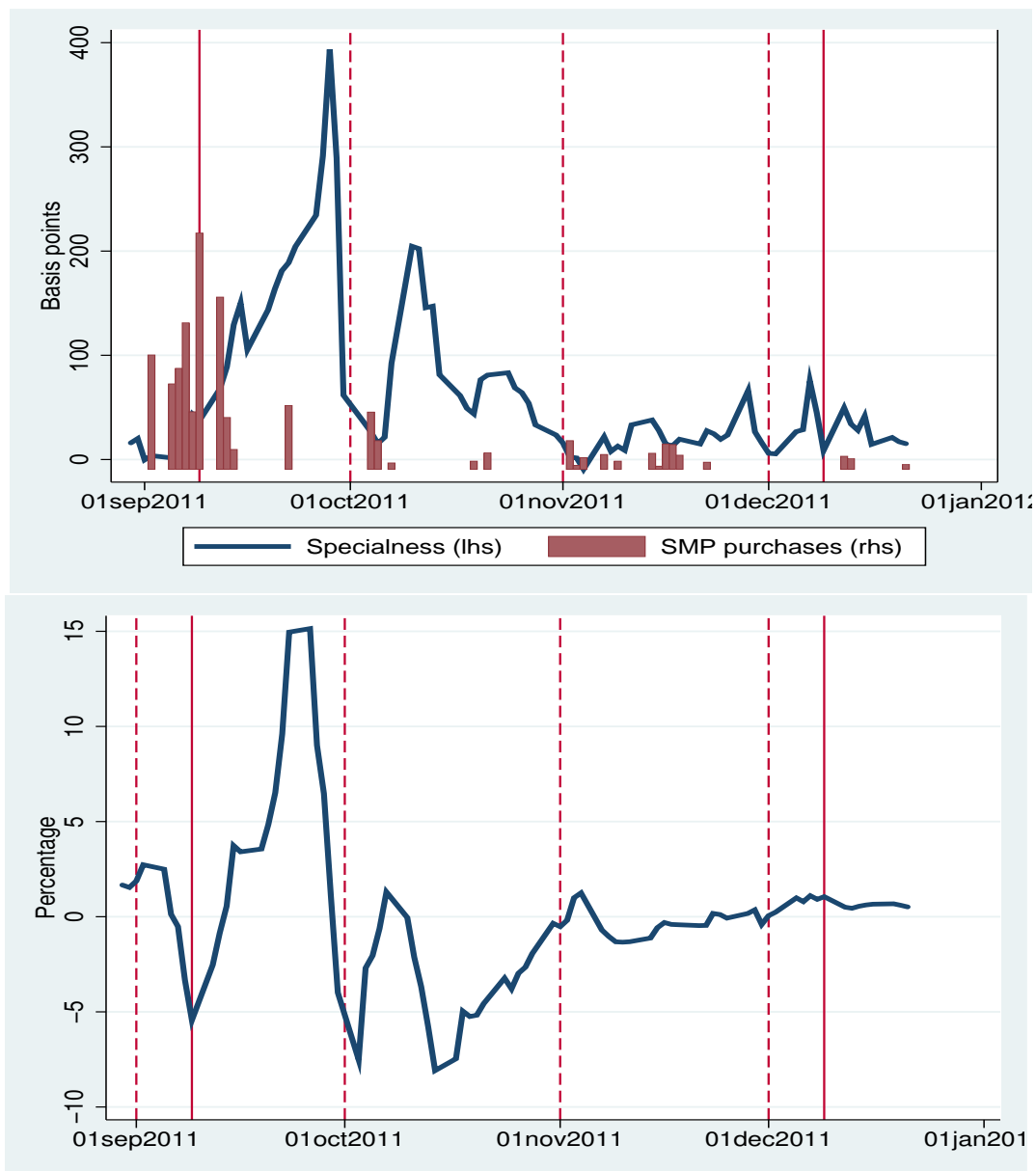


Fig. A-XI. **Specialness and repo imbalance for the 10-year on-the-run bond (IT0004759673)** - The figure shows the value of specialness (top panel) and of repo imbalance (bottom panel) calculated for the Italian sovereign bond with 10-year maturity (ISIN IT0004759673) that was on-the-run during the period of the SMP purchases. Specialness is calculated as the difference between the general collateral (GC) repo rate and the special repo rate on this benchmark security and it is reported in basis points (left-hand scale). Repo imbalance is the difference between the transactions initiated as special reverse repo and the transactions initiated as financing repo on the 10-year on-the-run security and it is reported in percentage points (left-hand scale). The bars reports the value of the on-the-run security purchased in the SMP portfolio. Continuous vertical lines indicate futures delivery dates. Dashed vertical lines indicate the dates of the primary issuance of the bond.

Table A-I: **Distribution of specialness** - This table reports the fractional distribution of specialness, the average, the standard deviation, the minimum and the maximum of the daily distribution. Specialness is in basis points and is based on spot next (SN) and tomorrow next (TN) repo transactions. The statistics are reported for the full sample and for three distinct sub-periods. First period from 1 October 2009 to 7 August 2011. Second period: from 8 August 2011 to 21 December 2011. Third period: from 22 December 2011 to 12 July 2012.

Specialness	Freq.	Mean	St.dev.	Min	Max
Full sample					
(0, 25] bps	0.852	8.280	6.059	0.000	25.000
(25, 50] bps	0.103	34.042	6.796	25.002	49.982
(50, 75] bps	0.024	59.897	6.956	50.002	74.984
(75, 100] bps	0.008	85.752	7.027	75.089	99.982
> 100 bps	0.011	173.981	96.899	100.002	1020.185
1st period					
(0, 25] bps	0.904	7.472	5.853	0.000	25.000
(25, 50] bps	0.069	33.534	6.679	25.002	49.974
(50, 75] bps	0.012	59.967	6.959	50.002	74.702
(75, 100] bps	0.004	85.402	7.225	75.110	99.763
> 100 bps	0.009	194.765	114.425	100.128	1020.185
2nd period					
(0, 25] bps	0.565	13.556	6.350	0.005	25.000
(25, 50] bps	0.294	34.642	6.913	25.005	49.982
(50, 75] bps	0.081	59.478	6.722	50.006	74.978
(75, 100] bps	0.029	85.585	6.869	75.089	99.982
> 100 bps	0.031	156.093	71.190	100.002	458.099
3rd period					
(0, 25] bps	0.887	8.577	5.353	0.000	24.984
(25, 50] bps	0.080	33.909	6.698	25.012	49.897
(50, 75] bps	0.020	60.902	7.473	50.013	74.984
(75, 100] bps	0.007	86.931	7.017	75.405	99.744
> 100 bps	0.005	133.025	37.885	100.875	282.754

Table B-I: Agent types

	Notation	Definition
High-valuation agent		
Buyer	\bar{b}	Fresh entrant and seeks to buy an asset
Lender	\bar{l}_i	Has bought asset i and seeks to lend it
Non-searcher & repo counterparty $\underline{s}i$	$\bar{n}\underline{s}i$	Has lent asset i to agent $\underline{s}i$
Non-searcher & repo counterparty $\underline{n}i$	$\bar{n}\underline{n}i$	Has lent asset i to agent $\underline{n}i$
Non-searcher & repo counterparty $\underline{b}i$	$\bar{n}\underline{b}i$	Has lent asset i to agent $\underline{b}i$
Seller	$\bar{s}i$	Has bought asset i and seeks to sell it
CB Buyer	\bar{b}^{cb}	Fresh entrant and seeks to buy an asset
CB Holder	$\bar{h}^{cb}i$	Has bought asset i and holds it
CB Seller	$\bar{s}^{cb}i$	Has bought asset i and seeks to sell it
Low-valuation agent		
Borrower	$\underline{b}o$	Fresh entrant and seeks to borrow an asset
Seller	$\underline{s}i$	Has borrowed asset i and seeks to sell it
Non-searcher	$\underline{n}i$	Has sold asset i
Buyer	$\underline{b}i$	Has sold asset i and seeks to buy it back and deliver it to lender

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