EUROPEAN CENTRAL BANK
EUROSYSTEM

Working Paper Series

Claus Brand, Lorenzo Ferrante, Antoine Hubert

From cash- to securities-driven euro area repo markets: the role of financial stress and safe asset scarcity

No 2232 / January 2019

Abstract

Focussing on repo specialness premia, using ISIN-specific transaction-by-transaction data of one-day maturity repos, we document a gradual shift from cash- to securities-driven transactions in euro area repo markets over the period 2010-2018. Compared to earlier studies focussing only on specific sub-periods or market segments we extend, illustrate, and validate evidence on financial frictions that are relevant in driving repo premia: controlling for a comprehensive range of bond-market specific characteristics, we show that repo premia have been systematically affected by fragmentation in the sovereign space, bank funding stress, and safe asset scarcity. These channels exhibit very strong country-specific differences, as also reflected by large discrepancies in country-specific interest rates on General Collateral. To ensure robustness of our empirical findings, we apply panel econometric and data mining approaches in a complementary and mutually informative way.

Keywords: Monetary policy, repo market, bond specialness, big data, machine learning.
JEL Classification: E52, E44, C33, C38.

At stake is the health of the 5 trillion-euro ($5.3 trillion) securities lending market, which greases the wheels of all manner of derivative, short-selling and structured transactions. [...] A crunch point has arrived in Europe. The last few days have seen an extreme spike in demand in particular for short-dated German government bonds. [...] Schatz and other short-dated core European government bonds have repriced from being accepted as "general collateral" to being increasingly "special". In order to borrow them in the repo market, firms have to pay up [...] (Bloomberg, 2016, November 18)

...of two otherwise identical instruments, that with the lower frictional costs of trading is the one more likely to be on special. (Duffie, 1996, p. 494)

Non-technical Summary

Euro area money market structures have been profoundly affected by the financial crisis, as a consequence of unconventional monetary policy measures, and changes in regulation. One important development is a structural shift from cash- to securities driven repo markets since 2010, with important implications for the implementation and transmission of monetary policy.

We analyse the drivers behind these changes in money market structures, with a specific focus on euro area repo markets over the period 2010-2018. We extend evidence of earlier studies that have focussed only on certain subperiods or market segments. We show how structural features of the bond market, funding stress, sovereign bond market tensions, and unconventional policies have affected interest rate spreads in repo markets. Systematic developments in these spreads point to inefficiencies in the pass-through of monetary policy through money markets that in the euro area are perpetuated because of market segmentation along jurisdictions emerging from different country risks and the scarcity of safe assets.

We focus on the spread between Special Collateral (SC) and General Collateral (GC) repo rates of one day maturity, with SC repo rates reflecting securities transactions in a specific security serving as collateral and GC repo rates reflecting such transactions based on a basket of securities. The former reflect the securities-driven side of repos, the latter the cash-driven or funding side. We use transaction-by-transaction, ISIN-specific data from automatic trading systems covering sales and repurchases of German, French, Italian, and Spanish bonds.

As for bond-market related characteristics, we illustrate the following impact on repo spreads: liquidity effects over bond-auctionning cycles incur specific time profiles in repo premia; country differences in the development of futures markets and their size relative to bond markets shape bond-specific benchmark characteristics which, in turn, drive specialness, a feature particularly visible in the German segment of the market; dates for delivering bonds into futures cause spikes in repo premia, particularly in jurisdictions where the future market is sizeable; Treasury bills generally carry significantly higher specialness compared to other bonds; term risk affects specialness.

As for macro-financial factors, observing that during the banking and sovereign debt crisis repo premia have been mainly driven by the GC repo rate, we document that widening repo spreads have reflected a high level of bank funding stress over the years 2010-11, its subsequent relief from the ECB's three-year longer-term refinancing operations as of 2012, and its flaring up again in the context of early repayments of funds obtained from these operations in the beginning of 2013. We show how, throughout these years, bond market stress and reversals appear to have as well contributed to higher repo spreads. Since 2015, following the launch of the ECB's Public Securities Purchase Programme, repo premia have been widening, reflecting that purchased bonds have become relatively scarcer. We show that this effect is not only related to the direct impact of purchases but also to indirect safe-asset

scarcity effects of PSPP operating at country- rather than bond-specific level. While the Eurosystem's Securities Lending Programme and its enhancement appears to have contributed to alleviate safe asset scarcity, the flatlining of repo premia since 2017 is likely also due to long-term investors having made larger shares of their securities holdings available for lending.

We illustrate our quantitative findings using standard data mining tools and test the average quantitative importance of specific transmission channels on the basis of panel-econometric regressions. We illustrate that in terms of detecting statistically robust patterns of interaction, as well as statistical fit, these methods are vastly superior to using panel regressions.

The disparities in repo rates have important consequences for monetary policy implementation and transmission: money market interest rates are no longer as firmly anchored to official central bank interest rates as before, even as large bond portfolios on central bank balance sheets might eventually be unwound. The asymmetries in repo spreads across countries indicate lingering market fragmentation along jurisdictions and a structural scarcity of safe assets, likely sustained by the phasing in of Basel III regulation. Defining operational targets for central bank operating procedures (even if only implicitly) demands confronting a conflict between the requirement for such benchmark rates to be sufficiently controllable and the need for benchmarks to be sufficiently liquid and sufficiently representative of funding conditions in interbank markets. Our findings suggest that all these requirements are today unlikely to be met simultaneously. These resulting divergences in funding conditions risk perpetuating differences in lending and borrowing conditions further along the monetary policy transmission mechanism.

1 Introduction and Overview

We provide a comprehensive characterisation of the transmission of funding stress, sovereign bond market tensions, and unconventional policies through euro area repo markets since 2010 and thereby document the gradual shift from a cash- to a securities-driven structure in these markets. This shift points to inefficiencies in the transmission of monetary poliy through money markets (similar to pass-through inefficiences in the US as identified in Duffie and Krishnamurthy (2016), but perpetuated in the euro area because of market segmentation along jurisdictions emerging from different country risks and the scarcity of safe assets).

Throughout our analysis we focus on two repo premia – which we refer to as *composite specialness premium* (the Special Collateral (SC) rate over the euro area General Collateral (GC) pooling rate)[1] and *bond specialness premium* (the SC rate over the country-specific GC rate). We use transactions data for one-day maturity repos and control for bond-specific features in a comprehensive way. Specifically, we use transaction-by-transaction, ISIN-specific data from automatic trading systems covering sales and repurchases of German, French, Italian, and Spanish bonds.

In Sections 2.1 and Annex A we illustrate how bond-market specific characteristics shape developments in repo markets: liquidity effects over bond-auctionning cycles incur specific time profiles in repo premia; country differences in the development of futures markets and their size relative to bond markets shape bond-specific benchmark characteristics which, in turn, drive specialness, a feature particularly visible in the German segment of the market; dates for delivering bonds into futures cause spikes in repo premia, particularly in jurisdictions where the future market is sizeable; Treasury bills generally carry significantly higher specialness compared to other bond; term risk affects specialness. In tracing developments and structural changes in the composite and the bond specialness premia over time, we control for these bond-specific features in an explicit way.

Observing that during the banking and sovereign debt crisis repo premia have been mainly driven by the GC repo rate, in Section 2.3 we document that widening repo premia have reflected a high level of bank funding stress over the years 2010-11, its subsequent relief from the ECB's three-year longer-term refinancing operations as of 2012, and its flaring up again in the context of early repayments of funds obtained from these operations in the beginning of 2013. Throughout these years, bond market tensions and reversals appear to have as well contributed to higher repo premia by exerting downward pressure on bond specialness premia in stressed countries and raising the premium of GC rates in stressed jurisdictions over those in non-stressed jurisdictions. Since 2015, after the launch of the ECB's Public Securities Purchase Programme (PSPP), repo premia have been widening, reflecting increasing pressure on bonds that, as a consequence of the purchases, have be-

[1]Specifically the Special Collateral rate over the Eurex GC Pooling ECB Extented rate. For more detailed information on how repo spreads have been constructed, please see Annex B.

come relatively scarcer, in particular so for the German and the French segments of the market (as also documented by Arrata, Nguyen, Rahmouni-Rousseau and Vari (2017) or, in relation to LSAP in the US, by D'Amico, Fan and Kitsul (2014)). We also identify increasing repo specialness on Treasury bills during this episode, although these are not bought under PSPP. The latter could be due to indirect consequences of the liquidity injected in the context of the ECB Asset Purchase Programme jointly with the special nature of Treasury bills being the closest substitutes for cash (in terms of liquidity and safety). Overall, we identify a prominent country-level scarcity effect, on top of scarcity at bond-specific level.

We estimate that funding stress as experienced during the years 2010-11 has caused a wedge between special rates and the country-specific GC rate of around 5-15 basis points (bps). Safe asset scarcity under PSPP appears to mostly play a role once holdings exceed about 10-15% of outstanding amounts of a country's bonds. The effects on repo premia are highly asymmetric across countries, with a systematic impact of around 10-20 basis points on composite specialness for French and German collateral. The Eurosystem's Securities Lending Programme and market adjustment have likely helped to attenuate this effect.

We illustrate these quantitative findings using standard data mining tools (regression trees and random forests), and test the average quantitative importance of specific transmission channels on the basis of panel regressions, as presented in Section 3. In terms of detecting statistically robust patterns of interaction, as well as statistical fit, these methods have proved vastly superior to using panel regressions.

Compared to earlier studies (focussing only on particular sub-periods or market segments) we analyse a more comprehensive sample and use a wider set of bond-market specific controls. As for the impact of central bank asset purchases on repo specialness our findings validate those by Arrata *et al.* (2017) for the period since the inception of PSPP and by Corradin and Maddaloni (2017) for specialness in the Italian repo market segment during the period of the ECB's Securities Markets Programme (SMP).

Our estimates are relevant for understanding the evolution in interest rate spreads across different money market segments, both when looking back as well as looking ahead (Section 4): as a consequence of the financial crisis, regulation, and structural market developments, there has been a profound shift away from unsecured lending in money markets towards secured lending. Lingering financial fragmentation in the collateral space, above all sovereign debt, and, as a consequence, scarcity of safe and liquid assets are likely to continue to cause sizeable disparities in interest rates across different segments of the money market. Thus, with the volume of unsecured transactions having become increasingly scarce, the growing depth of securities lending markets has not necessarily brought about a stronger convergence in interbank borrowing conditions.

Our findings validate and complement the fundamental mechanism expounded in Duffie (1996)'s seminal general equilibrium model of the repo market and its underlying cash market, positing that with the repo being a collateralised instrument, repo premia reflect inhibition in the availability of collateral arising from legal requirements or institutional and market structures. Specifically Duffie (1996) posits that for a given supply of securities, repo premia are driven by demand for short positions, constraints on the supply available, and the liquidity of the security: "…of two otherwise identical instruments, that with the lower frictional costs of trading is the one more likely to be on special" (Duffie, 1996, p. 494). In line with this fundamental mechanism, we stress that the driving frictions behind what over the past two years has been referred to as 'collateral crunch' is not on the side of liquid German instruments, but rather on the side of their complements being considered insufficiently safe and liquid. In this spirit, adding more specific details to the frictions listed by (Duffie, 1996) we point to the importance of safe asset scarcity arising from financial factors like sovereign bond market stress and flight-to-safety, or unconventional policies.

Disparities in repo rates have important consequences for monetary policy implementation and transmission: money market interest rates are no longer as firmly anchored to official central bank interest rates as before, even as large bond portfolios on central bank balance sheets might eventually be unwound. Defining operational targets for central bank operating procedures (even if only implicitly) demands confronting a conflict between the requirement for such benchmark rates to be sufficiently controllable and the need for benchmarks to be sufficiently liquid and representative of funding conditions in interbank markets. Our findings suggest that all these requirements are today unlikely to be met simultaneously. The resulting divergences in funding conditions risk perpetuating differences in lending and borrowing conditions further along the monetary policy transmission mechanism.

2 Repo premia and market developments since 2010

Over the last 15 years European money markets have undergone profound changes. The financial crises and, lately, regulation have accelerated a shift away from unsecured interbank lending as a source of funding to the secured market, or more precisely, to securities financing transactions (see Mancini, Ranaldo and Wrampelmeyer (2016) and the ECB's Money Market Surveys; see CGFS (2017) for a comprehensive description of repo market structures and development in the context of changing regulation and unconventional policies; specifically, as for the impact of regulation, see Bucalossi and Scalia (2016)).

A repo consists of two operations: selling securities against cash ('repo-ing out') as a funding operation and simultaneously repurchasing the same nominal amount of an equivalent security ('reversing in') as a securities sourcing operation.[2] Legally European repos convey collateral by title transfer, as opposed to US repos conveying collateral by security interest (where collateral is pledged, not sold).

This structure ensures low credit and liquidity risk for the buying side of the operation compared to an unsecured transaction. Credit risk is mitigated by liquidating collateral in the case of counterparty default or resorting to the repo counterparty in case the collateral issuer defaults. In principle, the buyer is therefore exposed to the risk of seller's default and, subsequently, to the decline in the price and liquidity of the asset. Conversely, the seller mainly faces market risk if the price declines (as she has to repurchase at original price). But the emerging dominance of CCPs in clearing repos has mitigated these risks and, throughout different phases of the crisis, helped to preserve access to repo markets also for banks in stressed jurisdictions.

One can distinguish two primary uses of repo.

1. Through cash-driven repos the seller finances long positions and buyers lend cash, based on a basket of security issues that are equally acceptable as collateral at the same repo rate (typically government securities with similar degree of risk).[3] As a money market instrument, its key determinants are the supply and demand for cash. The repo rate on such General Collateral repos is correlated with other money market rates and it is generally lower than corresponding unsecured rates as it carries lower credit risk.
2. Through securities-driven repos, sellers lend *special* (with one specific security serving as collateral) for cheap cash to enhance the yield on their portfolio and buyers can borrow securities to cover short positions. The yield enhancement effect reflected in repo premia can be seen either as additional dividend or as a shadow cost of long-term investors who are indifferent to providing repo collateral (Duffie, 1996). The key determinants of the Special Collateral repos are the supply and demand for a specific security issue, with the repo rate reflecting its scarcity.

Table 1 provides an overview of the frictions causing GC and SC repo rates to differ and refers to the relevant literature which studied them (in parenthesis). If there was no liquidity, credit or term risk and no other frictions, repo premia would be nil. Yet none of this is the case.

- On the cash side, funding pressure may drive up GC rates (faster than SC rates), in turn con-

[2] Standards for transactions in terms of purchased securities, equivalent securities, purchase and repurchase prices are stipulated in GMRA 2011 - the Global Master Repurchase Agreement.

[3] General Collateral baskets are structured by country, agency, and government debt. In Europe, Eurex is the provider of repos based on larger baskets also known as GC pooling repos. The Euro GC Pooling ECB Basket includes ECB eligible instruments of Central Banks, Central, regional and Local governments, Supranational institutions and "Pfandbriefe" of credit institutions and agency credit institutions rated not below A-/A3 while in the ECB EXTended basket one, instruments with rating up to BBB-/Baa3 are accepted. Other baskets: GC Pooling INT MXQ basket including foreign bonds and GC Pooling Equity basket defined by the European benchmark indexes (http://www.eurexrepo.com/repo-en/products/gcpooling).

Table 1: Financial frictions driving repo spreads

Cash driven: GC	Securities driven: SC
Funding Pressure	• Bond-market factors • Hedging, speculating, reversals (Duffie, 1996) • Liquidity and benchmark status • Term risk (Buraschi and Menini, 2002) • Market structure and regulation (CGFS, 2017; Bucalossi and Scalia, 2016) • Sovereign credit risk and flight-to-safety • Safe asset scarcity and scarcity from QE (Arrata *et al.*, 2017; Corradin and Maddaloni, 2017; D'Amico *et al.*, 2014)

tributing to a widening of repo specialness.

- Bond-market specific factors affect supply and demand for securities in important ways. Repos are frequently used for hedging and speculating on bond market reversals, concentrated in specific, highly liquid instruments. Specific liquidity effects (associated to benchmark status) emerge from bond-auctionning cycles and deliverability into futures, and are particularly concentrated in bonds being cheapest-to-deliver (CTD) for futures and options. Institutional factors, changes in market structures (e.g. end-of-period window dressing by lenders or increasing incentives for long-term investors to enter the market and make securities available), and regulation (e.g. bonds of HQLA status) also affect the supply of securities. Different term risk across bonds, as analysed in Buraschi and Menini (2002), also determines their relative demand in repo markets, and requires taking time-varying duration-specific characteristics of underlying collateral into account.

- Sovereign credit risk varies significantly across euro area countries and thereby accounts for cross-country divergences in repo premia. For instance, periods of sovereign bond market stress can put downward pressure on SC rates (e.g. as short positions are covered through bond sourcing in SC repo transactions).

- Finally, more recently, central bank asset purchase programmes in the context of unconventional monetary policies have further reduced the supply of securities readily available in the market (so-called 'free float' taking into account scarcity induced by buy-and-hold investors).

2.1 Relevance of and development in repos of one-day maturity

In Europe, one can distinguish three types of repo transactions: automatic transactions cleared by a CCP and characterised by bilateral collateral management (principal business model in Europe); automatic transactions cleared by a CCP and characterised by tri-party collateral management (business model particularly used in the context of GC transactions); direct transactions bilaterally cleared and characterised by bilateral collateral management.[4]

Since the beginning of the last decade, trading, clearing, and collateral management in Europe have increasingly been conducted through automatic trading systems (ATS), bringing together the provider of the ATS platform, clearing houses (CCPs), and collateral management agents. According to the ECB's Money Market Survey of September 2015,[5]direct and voice-brokered repos accounted on average for about 40% of total repo turnover between 2010 and 2015 while the remaining share has been traded via automatic trading systems (ATSs).

Market trading (especially for government securities) has become concentrated in few trading platforms: BrokerTec, a repo platform for European (except Italian) securities; MTS Repo, based in Italy and covering 90% of the Italian repo market; Eurex Repo, based in Germany, operating in the Euro Repo Market and leader in the Euro GC Pooling Market.

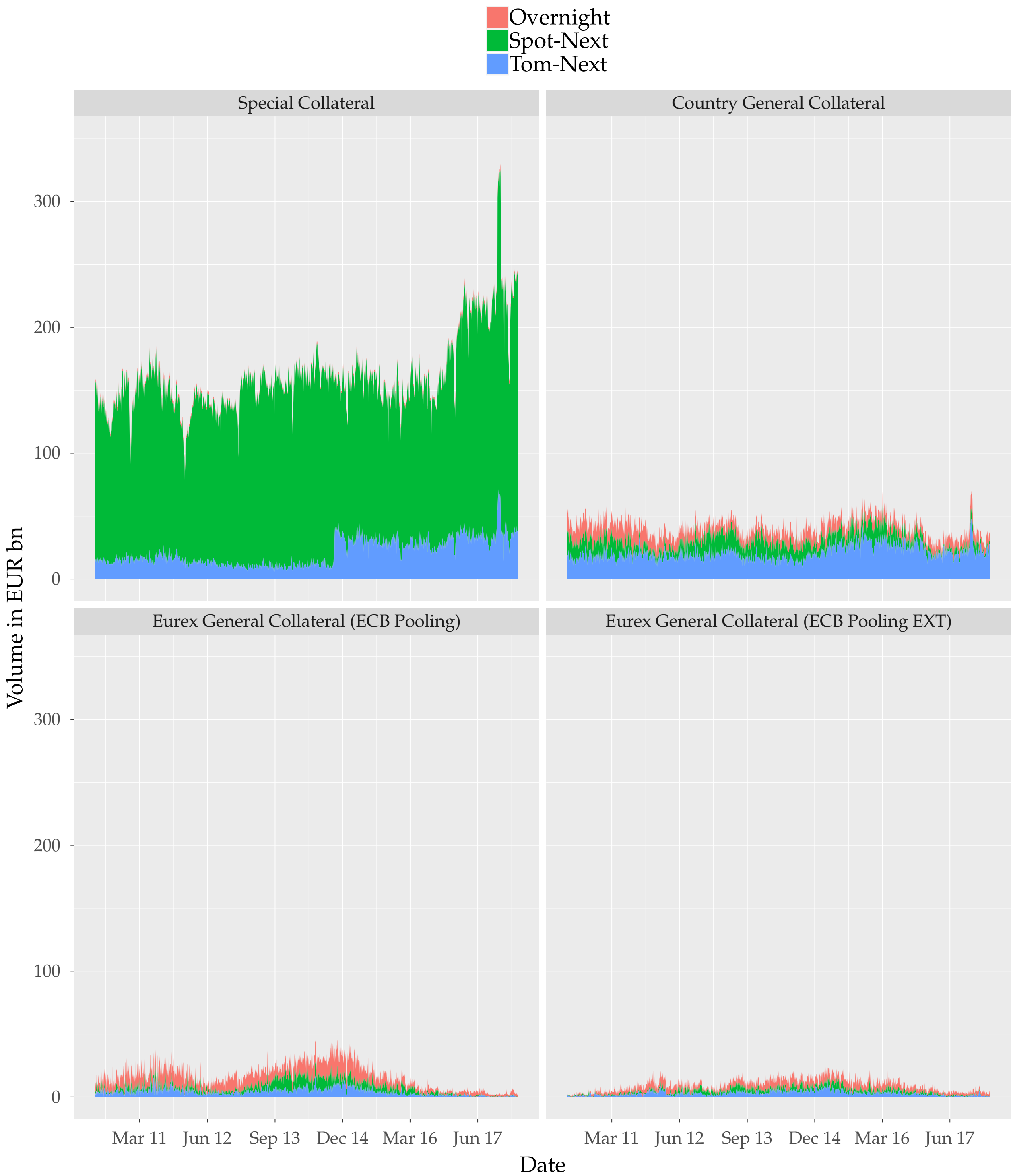
In our analysis we use transaction-by-transaction data from BrokerTec and MTS since May 2010. However, for the sake of completeness, transactions from Eurex are also added (starting from 2013) when illustrating total turnovers. We focus on repos of one-day maturity which on these platforms constitute about 95% of total volumes.

Figure 1 depicts trading volumes in repos of one day maturity for government bonds, as reported through these three trading platforms. We distinguish transactions by their settlement structure. GC repos are mostly settled on the next day ('tomorrow next') or two days after the transaction date ('spot next'). Special repo transactions are settled mainly two days after ('spot next') the agreement has been made, mirroring the settlement of transactions in bond markets. The high level of repo turnovers reflects an increasing importance of securities-driven transactions in the last years, particularly as of 2016.

[4]Old technologies are still used for bilateral trading. For example, telephone, electronic messaging systems and voice-broker systems allow counterparties to trade and arrange bilaterally the clearing and the collateral management phases. Currently, contrary to past practice, such bilateral transactions are no longer registered post trade with a CCP and assigned to a tri-party agent for collateral management.

[5]The survey is available through this link: https://www.ecb.europa.eu/pub/pdf/other/euromoneymarketsurvey201509.en.pdf

Figure 1: Daily turnover in one-day maturity repos by settlement type



Note: Special and Country General Collateral volumes are restricted to the jurisdictions analysed: DE, ES, FR and IT.
Source: BrokerTec, MTS, Eurex.

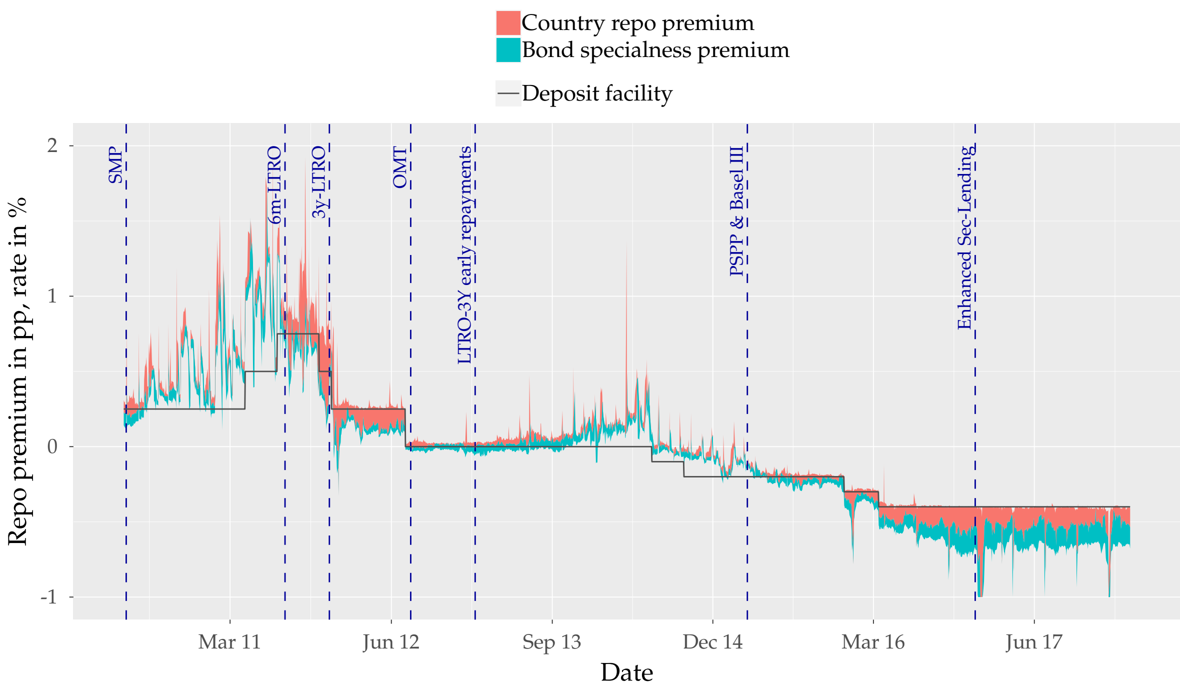
2.2 Repo premia and bond-market specific features

Bond-market specific features affect the securities-driven side of the repo market and thereby the bond specialness premium. As opposed to US bond and repo markets, in the euro area, such features relate to benchmark characteristics arising not only from bond-auctionning cycles, but also deliverability into futures. Specifically, benchmark status of the underlying instrument on the repo market relates to deliverability into futures basket rather than the bond being on-the-run or being tapped (Ejsing and Sihvonen, 2009). These characteristics vary across euro area countries depending on the depths of the futures market. Annex A provides a detailed overview of these features. Finally, Treasury bills generally carry significantly higher specialness compared to other bonds, in particular in the German segment.

2.3 Repo premia in the wake of the financial crisis and unconventional policies

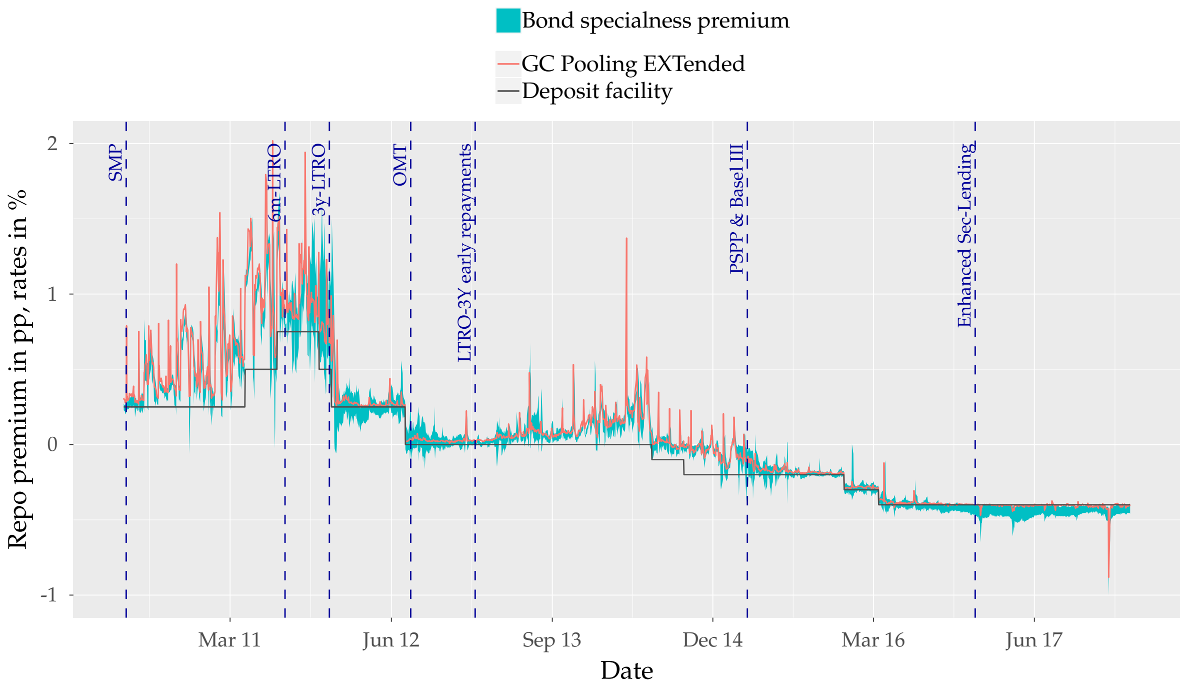
Figure 2 and 3 illustrate developments in country-specific repo spreads for German and Italian collateral since 2010, highlighting time instances of major ECB decisions on unconventional policies taken in response to the global financial crisis. The charts decompose the composite specialness premium (the spread of the GC Pooling ECB EXTended rate over special rates) into a "country repo premium" (the spread of the GC Pooling ECB EXTended rate over the country-specific GC rate) and a "bond specialness premium" (the country-specific GC rate over special rates).

Figure 2: Repo premia developments on German collateral



Note: For better visualisation rates below -1.0 pp are capped at -1.0 pp. *Source:* BrokerTec, MTS.

Figure 3: Repo premia developments on Italian collateral



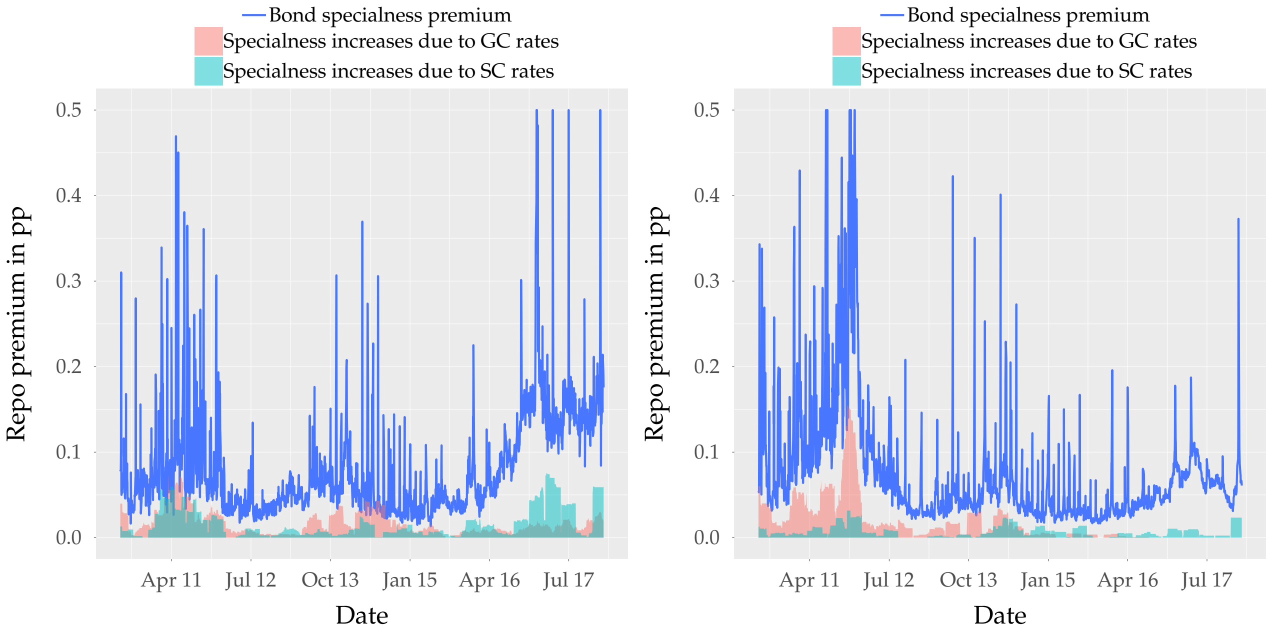
Note: For better visualisation rates below -1.0 pp are capped at -1.0 pp. *Source:* BrokerTec, MTS.

Two observations stand out from these figures: first, there are protracted systematic movements in repo premia over time, concentrated in the period 2011 and 2012 (the banking and sovereign debt crisis) and as of 2016 – within the period of PSPP; second, especially during these episodes, a country repo premium is prevalent on German collateral (and French, not shown) and negative or close to nil for Italian collateral (and Spanish, not shown), reflecting that especially German government bonds have been trading at a premium relative to the euro extended basket of securities, due to their safe haven status.

Repo premia arise from factors affecting either cash-driven transactions (with GC rates moving particularly up) or securities-driven ones (with SC rates going down, recall Table 1). Figures 4a and 4b illustrate the extent to which changes in bond specialness have been driven either by the cash or the securities side, i.e. reflecting movements primarily in the country-specific GC rate (market by red bars) or in the ISIN-specific SC rate (marked by turquoise bars).[6]

[6]In these figures, the measure of specialness increases arising from SC rates is the 60-days centered rolling average of the series of specialness changes for dates on which the decrease in the SC rate was higher than the GC rate. Analogously, days when the GC rate has gone up at a higher pace than the SC rate are considered for the measure of specialness increases arising from GC rates. Only changes in specialness above 1 basis point are considered and the pace of change in a rate is considered higher than its counterparty if the absolute change in the first is at least twice as large as the absolute change in the second.

Figure 4: Cash versus securities-driven side of bond specialness premia



(a) German segment (b) Italian segment

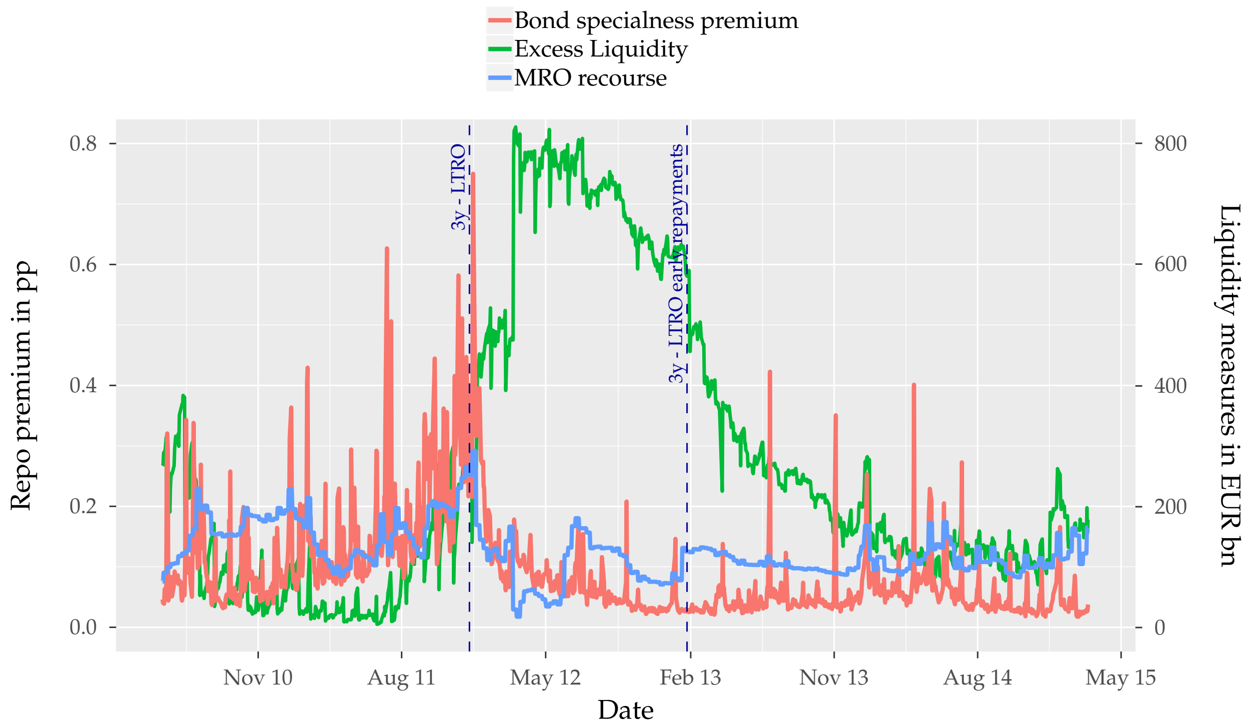
Note: For better visualisation spreads above 0.5 pp are capped at 0.5 pp.
Source: BrokerTec, MTS.

2.3.1 Bank funding stress and sovereign fragmentation

Figures 4a and 4b illustrate that from the start of our sample until the implementation of the 3-year LTROs, increases in bond specialness were mainly characterised by upward pressures on GC rates. During this period, bond specialness has been high in every country likely due to a high level of funding stress in the banking system, also testified by the upward trend in the total stock of MRO recourse despite other liquidity-providing measures having already been in place (6-month and 12-month LTROs). The implementation of the 3-year LTROs at the beginning of 2012 marked a clear break: specialness slumped sharply. For Italian bonds a further marginal decline in specialness continued until the ECB announced OMT (Outright Monetary Transactions) in summer 2012. The subsequent quiescence in specialness premia across countries ended once counterparties opted to start repaying funds obtained through 3-year LTROs as of February 2013 prompting aggregate excess liquidity in the system to decline (see Figure 5).

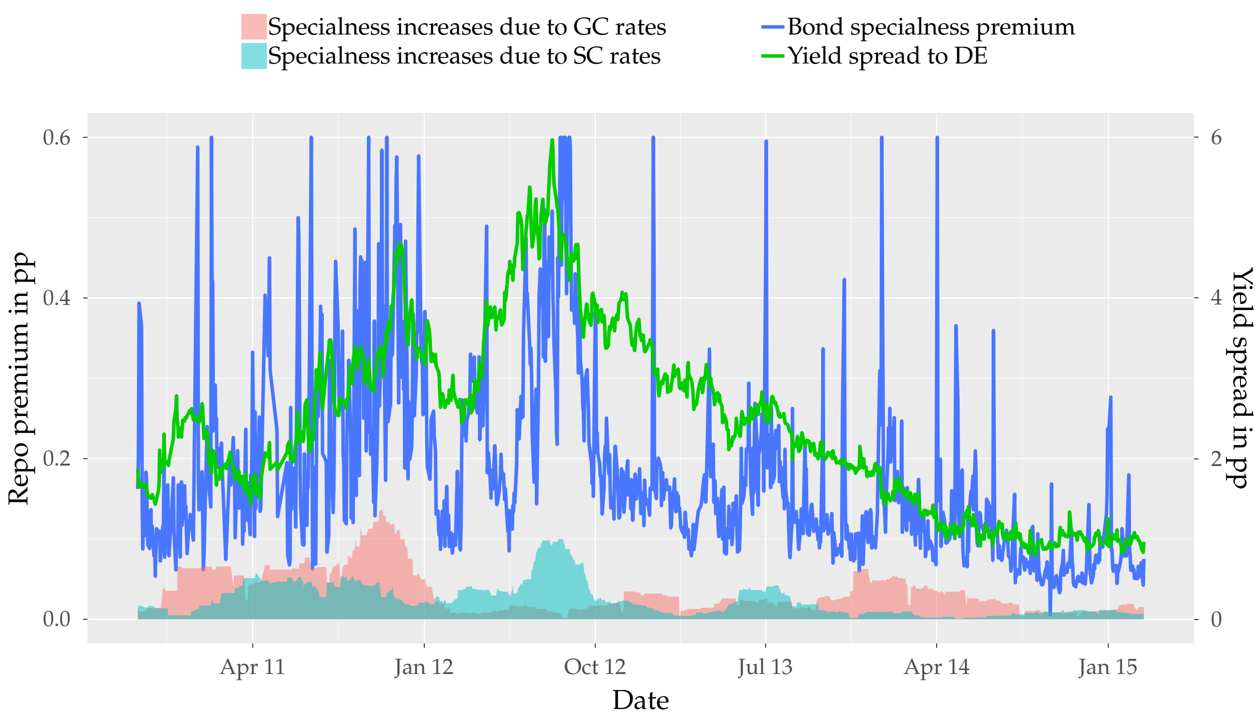
While prior to 2015 repo markets appear to have been primarily cash-driven and characterised by funding pressures, fragmentation in the sovereign space has also affected repo premia dynamics. For Spanish bonds, Figure 6 illustrates that repo specialness premia became driven by the securities side and increased dramatically in line with sovereign risk through much of 2012 when the country's savings banks crisis deepened and the government started restructuring its banking sector under EFSF/ESM Programme.

Figure 5: Funding stress, funding support, and bond specialness premia: Italian segment



Note: For better visualisation spreads above 0.75 pp are capped at 0.75 pp.
Source: BrokerTec, MTS.

Figure 6: Dynamics in bond specialness premia and market reversals: Spanish segment



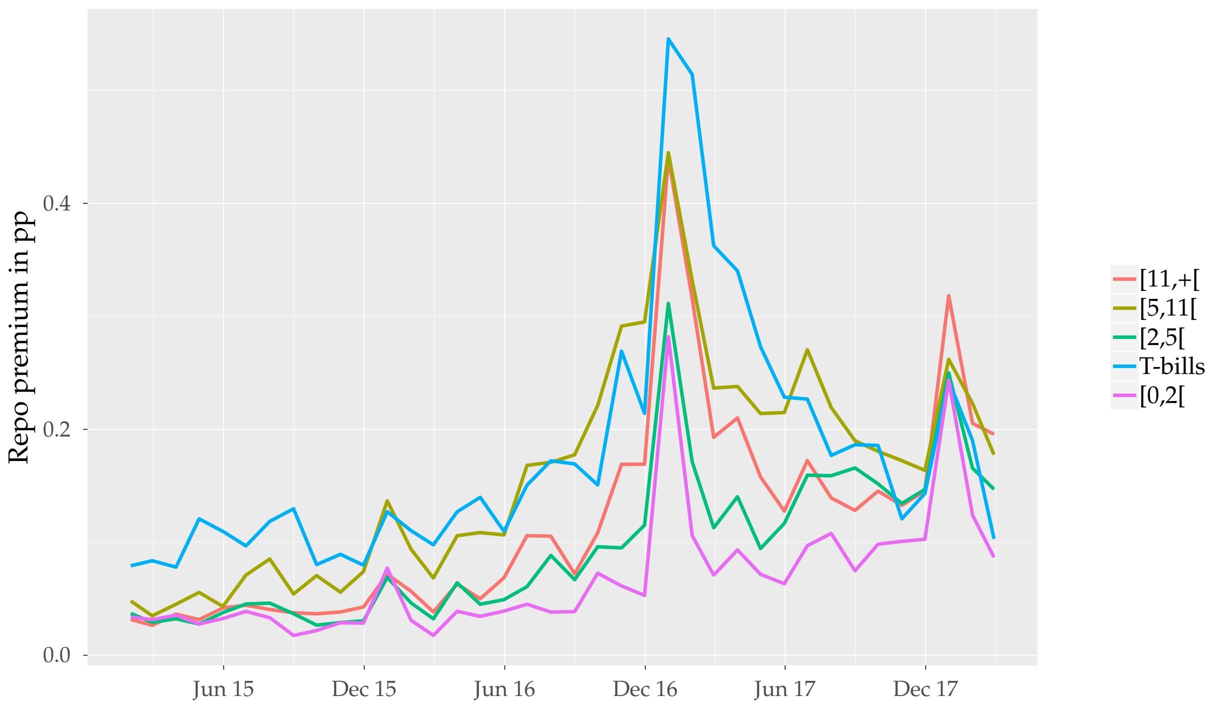
Note: For better visualisation spreads above 0.6 pp are capped at 0.6 pp.
Source: BrokerTec, MTS.

2.3.2 Safe asset scarcity

Since mid-2015, the securities-driven side has been dominating movements in repo premia (Figures 4a and 4b). The gradual shift from cash- to securities-driven repos, notably towards 'safer' jurisdictions (Germany and France), can be related to the progressive change in the regulatory framework (with the introduction of Basel III) and the implementation of the public sector purchase programme (PSPP) in March 2015.

As PSPP implementation progressed, repo premia rose systematically. Figure 7 provides an overview of bond specialness premia since the start of the program in the German segment of the market. Especially after 2017, we observe a decrease in the post-PSPP dispersion of specialness premia across maturities. The high specialness observed in instruments that have *not* been purchased under PSPP, like Treasury bills, is an exception to this pattern – possibly a consequence of indirect effects from PSPP and pointing to transmission of scarcity effects at country (on top of bond-specific) level.

Figure 7: Scarcity, and bond specialness by maturity buckets: German segment



Note: Bond specialness is averaged over buckets of residual maturity (with the exception of T-bills).
Source: ECB, BrokerTec, MTS.

Changes in regulation under Basel III have been widely considered to contribute to curtailing bond supply over this period: the Leverage Ratio can contribute to increase balance sheet costs of repos and thereby discourage repo exposure; even if banks may not be constrained by it, they have an incentive to 'window-dress' quarter-end disclosure of their Leverage Ratio, thereby reducing repo market activity on these dates; the Liquidity Coverage Ratio bolsters demand for high-quality liquid assets, strengthening safe-asset scarcity effects from financial stress and central bank asset purchases; the Net Stable Funding Ratio incentivises a shift from shorter to longer-term tenor in repo operations. Yet, results from trying to quantify these effects have been mixed (CGFS, 2017; Bucalossi and Scalia, 2016).

Concomitant with the enhancement of the ECB's Securities Lending Programme in late 2016, aiming to address securities shortages in repo markets, repo market premia (particularly bond specialness) have flatlined. Structural adjustments of the market will have also contributed to mitigate market squeeze, in response to the extraordinary year-end spikes in repo premia witnessed in December 2016. While such spikes in repo premia have made it more expensive to source securities, with the possible consequence of inhibiting market making and bond market liquidity, incentives have also been higher for long-term investors like insurance companies, pension funds and other large funds to enter the repo market as suppliers of securities, thereby enhancing the return on their portfolio.

3 Quantifying the impact of drivers of repo specialness

3.1 Measurement of repo premia and their drivers

3.1.1 Composite and bond specialness premia

In order to quantify the impact of repo market drivers presented in Section 2, our analysis focuses on the explanation of two repo premia: the bond specialness premium and the composite specialness premium (the latter being the sum of the country repo premium and the bond specialness premium as presented in Section 2.3). This distinction is important, because market fragmentation in the sovereign space causes sizeable differences in country-specific GC repo rates and in the corresponding spread over the Euro GC pooling EXTended repo rate (the country repo premium). As illustrated in Section 2.3, country repo premia are stable and close to nil in the Italian and Spanish segments. Hence, for the composite specialness premium we will present results only for German and French collateral.

Our study covers one-day maturity repo transactions on German, French, Italian and Spanish government bonds over the period 10 May 2010–28 February 2018. We chose these four jurisdictions on account of the large size of their repo markets and their differences in bond market characteristics.

Following the methodology by Corradin and Maddaloni (2017), we match around 15 million SC transactions with 1.2 million GC repos to construct bond specialness premia. The composite specialness premium is instead computed as the spread between the time series of the GC ECB EXTended Pooling and the ISIN-specific time series of SC rates. For a more comprehensive description of the matching methodology and of the data used in this study, see Annex B.

3.1.2 Empirical proxies capturing drivers of repo premia

Table 2 provides an overview of proxies that can be used to analyse the impact of financial factors on repo premia as posited above in Table 1.

Table 2: Overview of factors and indicators on securities and cash side of repos

Factors driving the cash side of repos	
Financial variables	Possible proxies
Funding stress	Aggregate recourse to MROs; EA level of excess liquidity; Euribor-OIS spread.
Factors driving the securities side of repos	
Financial variables	Possible proxies
Asset scarcity	Complement to the free-float measure: Eurosystem holdings over outstanding amount at bond and country level; Share of price insensitive investors' bond holdings (from the Securities Holding Statistics); Eurosystem collateral absorption in the context of refinancing operations.
Flight-to-safety	First principle component of maturity-specific yield spreads of Italy and Spain to Germany and France respectively.
Country risk	Maturity-specific yield spreads of France, Italy and Spain to Germany.
Bond Auctionning cycles	Dummies for the 15 days preceding a bond issuance and 15 days following issuance (including the issuance date); same dummies around tapping; interaction of bond-auctionning time-dummies and dummies for the on-the-run bond and the tapped bond.
Futures market	Dummy for the CTD bond in each future contract basket; interaction of this dummy with a time-dummy capturing the two days preceding delivery date and the delivery date.
Term risk	15-days moving average of the changes in the OIS 3m3m interacted with bond type dummies; bond-specific modified duration.
Structural market changes	Dummy for implementation of enhanced Securities Lending facility. Dummies for end of maintenance periods (in the cash-driven period), quarter-ends and year-ends reflecting window dressing; time-fixed effects.

As for measuring funding stress, the EURIBOR-OIS spread is a natural candidate. Alternatively, specifically for the pre-APP period, excess liquidity can also be used as a proxy for funding constraints under fixed-rate full allotment, as implemented by the ECB following the demise of Lehman

Brothers in September 2008: in the absence of funding constraints, liquidity would be redistributed in an effective way and counterparties would ultimately bid for aggregate liquidity to be neutral eventually. Yet with the inception of PSPP the increase in excess liquidity no longer reflects funding constraints. Another proxy would be the aggregate recourse to the main refinancing operations (MROs) as it reflects refinancing needs by funding-constrained counterparties in an environment of excess liquidity.

As for factors driving the securities side, we distinguish between proxies capturing asset scarcity, flight-to-safety, country risk, liquidity effects over bond-auctionning cycles and in relation to the futures market, term risk, and structural changes in the market. Asset scarcity is measured by the share of bond- and country-levels Eurosystem holdings relative to their respective total outstanding amounts, by the share of holdings in the hands of buy-and-hold investors and by a measure of collateral absorption induced by the Eurosystem refinancing operations. Flight-to-safety and country risk proxies are derived from various yield-spread metrics as indicated in the table.

As for bond-specific features, we capture liquidity effects from benchmark characteristics related to deliverability into futures and bond-auctionning cycles, controlling for bond type, modified duration (to proxy time-varying, bond-specific term risk), residual maturity and seasonal effects.

Interest rate reversals are proxied by the changes in short-term rates, but interacted with a dummy for Treasury-bills.

Finally, structural changes such as the change in modalities of the Eurosystem's Security Lending Facility are also captured through specific dummies and time-fixed effects.

3.2 Exploring the feature space

Throughout our study we have been using classical statistical learning or data-mining methods and panel econometrics in a complementary and mutually-informative way, the first to visualise the data, explore the importance and hierarchy of predictors, and to inform panel regression specifications, the second to test the quantitative linear impact of predictors. Results from both strategies have proved to be qualitatively consistent, but some quantitative differences emerged for certain covariates that exert non-linear effects – a consequence of difference in methodology. While we have run panel regressions as pooled regressions or including bond- or time-fixed effects, we have always included time-fixed effects in data mining tools (see Annex C.3). Overall, applying data mining tools has proved to provide a vastly superior statistical fit of our data than panel econometric methods – while avoiding overfitting and capturing robust relationships in the data (see again Annex C.3 for a comparison of statistical fit).

Data mining or machine learning tools have increasingly been employed in economics and finance, especially since the advent of large micro-data sets (for a review see Athey (2018), Sirignano, Sadhwani and Giesecke (2018)). These methods eschew searching for relevant interactions in large, noisy data sets through a cumbersome visual inspection or panel regression analysis seeking to improve fit and explanatory power in a haphazard manner.

For the purpose of our analysis, once the data have been extracted, checked for consistency, and cleaned, statistical learning methods have been invaluable to explore and quantify robust patterns of interaction in the data in a largely automatic and transparent manner, to establish a robust hierarchy of importance amongst the regressors, to identify non-linear relationships and, eventually, to support variable selection among highly correlated potential predictors. By capturing non-linearities and interactions across predictors, data-mining methods allow for more flexible and complex relationships than linear regression approaches and thereby achieve a significantly better fit of the data.

In our study, we have been largely relying on *regression trees* and *random forests*.[7] Originating from Breiman, Friedman, Olshen and Stone (1984), regressions trees recursively stratify the feature space into distinct regions (according to predictive power) until a minimum number of observations falling into any of these regions is reached. The goal is to identify regions that minimise the fitting error. To avoid over-fitting local features of the data, various cross-validation methods exist in order to improve the out-of-sample prediction accuracy of simple trees. A common method is 'pruning' (imposing cost of complexity on large trees, cutting some of the nodes, while still improving out-of-sample prediction). An alternative particularly robust method employed in the literature is to build random forests (Breiman, 2001) by growing different, decorrelated trees by randomly selecting only *subsets* of predictors at each split. Individual trees are grown on bootstraps of data.

A random forest prediction averages over the various regression trees. The approach of decorrelating the trees will hinder a strong predictor to always be in the top split and reveal a more robust picture of the importance of correlated predictors. The bootstrap allows statistical inference to be made on the importance and on the impact of predictors in a non-parametric way.

Annex C provides further information on the construction and calibration of regression trees and random forests with our data. Specifically, we invite the reader to go through Annex C.1 for illustration: it displays two simplified and pruned regression trees with bond specialness as dependent variable, one for Italian collateral during the pre-PSPP period and one for German collateral over the PSPP period. This Annex serves to illustrate key aspects of how to assess variable importance, hierarchies, and non-linearities on the basis of regression trees which, in turn, are an essential stepping stone for growing the random forests used for statistical inference as presented in this section.

The pruned regressions trees illustrated in Annex C.1 show that, in the pre-PSPP period, our

[7] For a comprehensive exposition of these specific methods see Varian (2014), James, Witten, Hastie and Tibshirani (2014), and Friedman, Hastie and Tibshirani (2001).

proxies for funding stress (particularly MRO recourse) and sovereign bond market stress are identified as predominant factors. Conversely, during the PSPP period, funding stress proxies do not appear high in the tree; measures of country-level and bond-level scarcity, jointly with bond specific characteristics, are dominant factors in explaining bond specialness. A threshold in German bond specialness is identified when total Eurosystem PSPP holdings of German government bonds exceed 13% of total outstanding amount.

Random forests can support variable selection through *variable importance plots*. They depict, for each variable, the loss in explanatory power from permutating observations of that variable (i.e. artificially "distorting" realised observations of that variable). The higher the loss according to this metric, the higher is the explanatory power of the variable in question.

Figures 24 to 27 in Annex D present variable importance plots for bond specialness over the entire sample period, but separately for each country. Among the measures of funding stress, excess liquidity ranks high (particularly in core jurisdictions) and – over the entire sample period – captures funding stress as well as liquidity injections from PSPP. Due to this convoluted nature of excess liquidity we chose to exclude it from further analysis, so as to achieve a better separation of the funding channel from PSPP effects. MRO recourse is important across jurisdictions and particularly for repos on Italian and Spanish collateral where bond specialness has been the highest during the funding stress period. For sovereign bond market stress, both measures of flight-to-safety for core jurisdictions and the yield spread (to Germany) are considered important, together with the first and second principal components of the yield curve spread. Proxies for PSPP-induced bond scarcity rank prominently. Bond-level scarcity implied by PSPP is more relevant than the country-level one in explaining bond specialness and the share of price insensitive investors' holdings adds also valuable information. Our metric of collateral absorption from Eurosystem refinancing operations ("Euro collateral pool") ranks very high for all countries – it likely reflecting the funding relief side from these operations as well as a scarcity effect on the asset side.

3.3 Quantitative results

We assess the quantitative impact of financial factors on both the bond specialness premium and the composite specialness premium using panel regressions as well as *partial dependence plots* from random forests (Friedman (2001)). Partial dependence plots measure the average impact of single predictors on the dependent variable conditional to the average effect of all other predictors.

Table 7 and Table 12 provide a comparison of pooled regression results across countries, for the bond specialness and for the composite premium, respectively. For each country, Tables 8–11 (again for the bond specialness premium) and Tables 13–14 (again for the composite premium) show three different versions of country-specific panel regressions: pooled regressions, regressions with time-fixed effects, and regressions with bond-fixed effects.[8] Standard errors, reported in parentheses, are robust to heteroskedasticity in bond and time dimensions. These tables report regressions including or excluding a proxy for the share of holdings from price-insensitive investors (denoted "bond-insensitive share") – but with the former covering a sample period starting only in January 2014 and thus not representing a complete picture over time.[9]

Figures 8–13 display partial dependence plots obtained from random forests. The figures display the cumulative impact of predictors on repo premia (normalised in terms of deviations from the average premium estimated if the respective predictor equals its lowest realisation). Readings on the y-axis are to be interpreted as cumulated partial effects of the regressor on the corresponding repo premium.

Across countries, the estimates confirm the quantitative importance of four channels affecting repo specialness premia: bond-market specific features, funding stress, fragmentation in the sovereign space, and safe asset scarcity.

3.3.1 Bond-specific and time controls

Bond-specific factors refer to both time-invariant and time-variant features: as for time-invariant characteristics, we control for the specific bond type in each country in a granular way (e.g. BOT, CTZ, CCT and BTP in Italy; Bubill, Schatz, Bobl and Bund in Germany). We take into account maturity at issuance and coupon type of the bond (i.e. zero coupon, fixed coupon, inflation-linked coupon or floating rate coupon). These controls capture the structural behaviour of repo premia on Treasury bills described in Annex A, Figure 19, as well as any structural variation in the cross-sectional dimension of repo premia such as constant liquidity premia in specific types of bonds or constant unobservable market preferences for given groups of bonds.

Time-variant bond controls capture properties such as the underlying bond's benchmark status, it being affected by deliverability into futures, cheapest-to-deliver, on-the-run or off-the-run status; specifically, these controls capture behaviour in repo premia of on-the-run and tapped bonds over the respective bond-auctionning cycle and of CTD bonds in the last days of trades in the future market. Additionally, modified duration, remaining maturity, and an interaction between policy rate expectations and Treasury bills are part of this set of time-varying controls too. Finally, time controls also capture seasonal effects, window dressing, and structural changes (e.g the enhancement of the Eurosystem Securities Lending facility).

[8]Only a restricted number of predictors of interest is included in the tables – the rest is being referred to in the main body of the text. Time-invariant bond controls (e.g. bond type and coupon type) are excluded from the bond-fixed effects regressions and, similarly, time controls (e.g. end-of-year and auctionning cycle dummies) are excluded from the time-fixed effects regressions.

[9]Random forests are flexible enough for us to use the full sample with missing observations of the holdings by price-insensitive investors set to zero.

Table 3 below provides an overview of these control variables and the acronyms referring to them in regression tables and figures.

Table 3: Panel regression controls

Bond factors	
Factors	Controls
Type and Initial Maturity	Dummy for each homogeneous group of bonds in terms of country, type and maturity at issuance
Coupon type	Dummies: "Fixed coupon", "Floating coupon", "Inflation-linked"
Benchmark features	Dummy: "On-the-run"
Futures market links	Dummies: "Deliverable bonds","CTD","CTD around delivery"
Bond auctionning cycle	Dummies: "Pre-issuance", "Post-issuance", "Pre-tapping", "Post-tapping". Interacted with benchmark candidates' dummies (on-the-run, deliverability and CTD) corresponding to the same maturity bucket
Residual Maturity	Dummies for yearly buckets of residual maturity and "Residual Maturity" in the RFs
Modified Duration	"Modified duration"
Hedging on rate expectations	"Interest rate reversals"
Time factors	
Factors	Controls
Seasonal effects & Window dressing	Dummies: "End-of-year", "End-MPs", "Last-of-quarter", "End-of-year"
Structural market changes	Dummy: "Enhanced SecLend"

Note: For more details on the construction of control variables, please see Annex B.

To save space, we do not report the coefficients of all bond controls in detail.

As for modified duration, especially for regressions over the 2010-2018 sample, our estimates validate that term risk, if measured by modified duration, reduces repo specialness premia (Table 7). But the impact is small – lower than 0.5 bp for a unit change in modified duration.

The interaction variable between our proxy for interest rate reversals and the Treasury bills dummy is associated with significant and positive coefficient estimates in the pooled regressions on the full sample, particularly for the German segment confirming that core short-term instruments are vehicles for hedging against and speculating on interest rate changes in the euro area.[10]

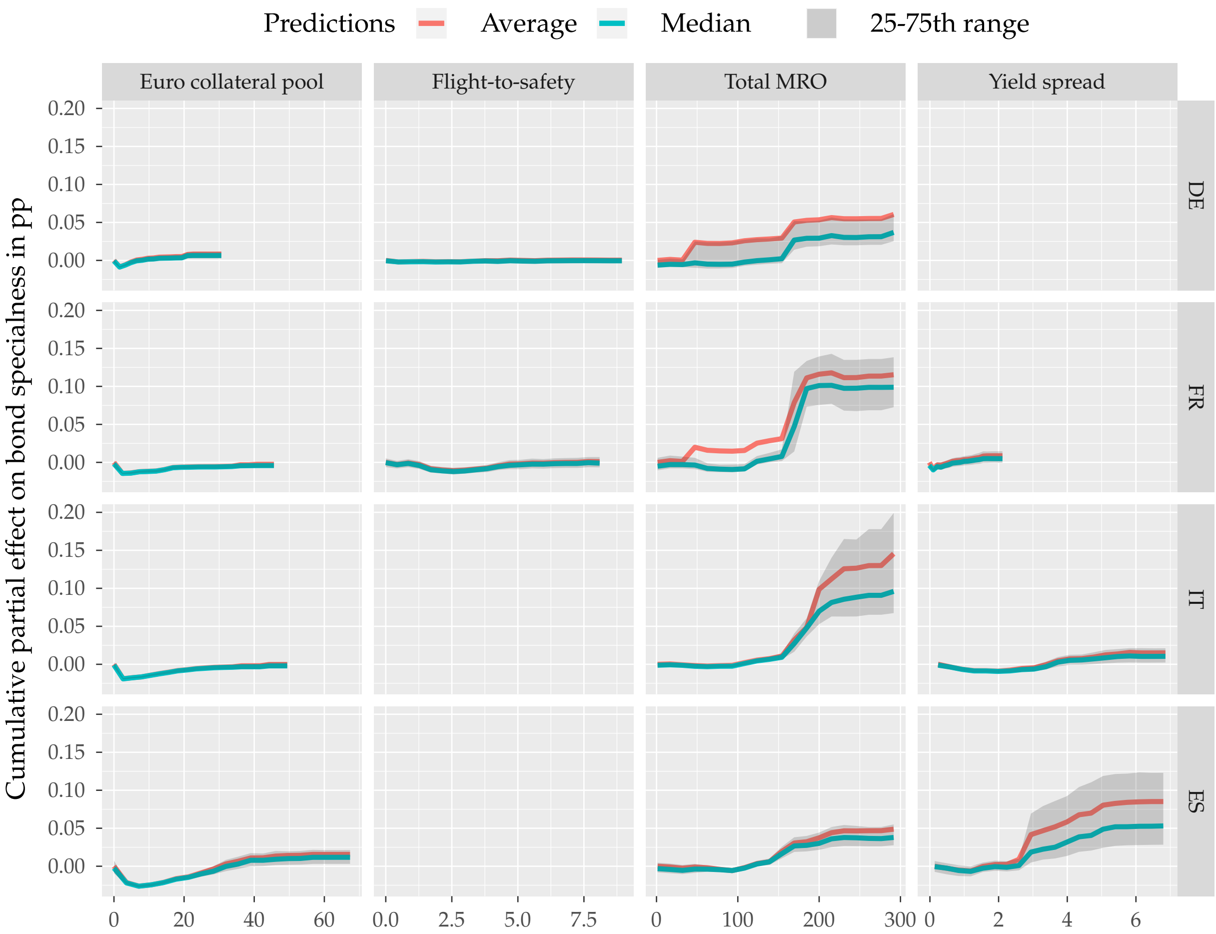
[10] For the shorter sample 2014-2018 (see section 3.3), the evidence is more ambiguous, likely owing to interest rate reversals being less prevalent over that period.

3.3.2 Bank funding stress and sovereign fragmentation

In quantifying the impact of funding stress on composite and bond specialness premia we mainly rely on the total stock of main refinancing operations (MRO) as a metric for funding stress (due to its high ranking in terms of variable importance), rather than excess liquidity (due to its convoluted nature in capturing the cash, as well as the indirect PSPP-related securities side of transactions).

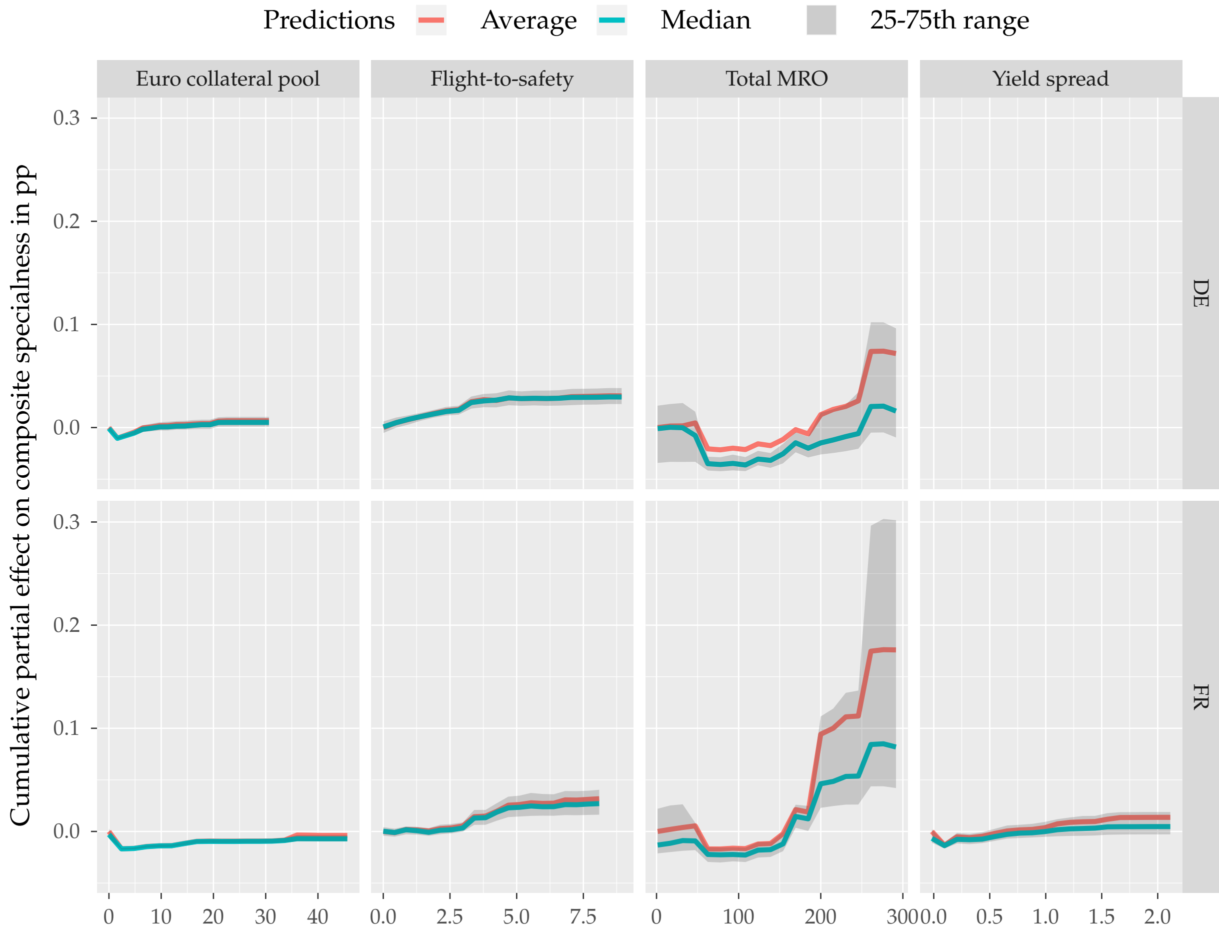
Two findings stand out: First, funding stress has widened repo premia on French and Italian collateral much stronger than on German collateral (Figure 9 and Table 7), with the linear effect on composite specialness estimated to be higher than on bond specialness, according to panel regressions (see Tables 12–14). Second, the funding stress impact appears to be non-linear, rising strongly once MRO recourse exceeded € 160 bn (Figure 9), which is why the panel regressions feature a dummy for high MRO recourse ("Large MRO" in Tables 7–14).

Figure 8: Partial dependence plots for the effects of funding and sovereign stress proxies on bond specialness



Note: Horizontal axes: Euro collateral pool expressed in %, Flight-to-safety in pp, Total MRO in € bn, Yield spread in pp. Partial dependence predictions are presented for the average tree (the forest) and for the trees corresponding to the first, second, and the third quartiles.

Figure 9: Partial dependence plots for the effects of funding and sovereign stress proxies on composite specialness



Note: Horizontal axes: Euro collateral pool expressed in %, Flight-to-safety in pp, Total MRO in € bn, Yield spread in pp. Partial dependence predictions are presented for the average tree (the forest) and for the trees corresponding to the first, second, and the third quartiles.

Sovereign bond market stress has affected premia on French collateral, and in particular, premia on German collateral through flight to safety; and on Italian collateral, and particularly, Spanish collateral directly. The importance of the country premium as a driver of the composite spread is reflected in a higher impact of flight-to-safety on the composite spread than on bond specialness (see Tables 8 and 9 and second column in Figures 8 and 9), suggesting a strong responsiveness in the spread of the German and French GC repo rate over the Italian and Spanish GC repo rate.

Absorption of available collateral through Eurosystem refinancing operations ranked prominently in terms of variable importance hierarchy. The amount of German bonds pledged as collateral is generally lower than that of other bonds (reading along the x-axis in Figures 8 and 9), reflecting substitution effects within the collateral pool and cross-country asymmetries in MRO and LTRO takeup over the various phases of the crisis. In the German segment, a positive impact of collateral absorption on specialness premia kicks in earlier and more coherently. Within the other segments, only Spanish premia turn positive once more than 30% of collateral have been absorbed. Overall, considering the ambiguity of the direction of impact from the amount of bonds pledged in refinancing operations (as also evident from the regressions), there is no coherent evidence that collateral absorption through Eurosystem funding support would have encumbered these assets. While for the German segment, such an impact is measurable, it is small.

3.3.3 Safe asset scarcity

The start of the Public Sector Purchase Programme accelerated the shift from cash to securities-driven markets. Asset scarcity induced by the purchase programme has been an important factor in explaining the widening of both composite and bond specialness premia.

We capture scarcity effects through the share of Eurosystem bond holdings over outstanding amounts at bond specific level ("Bond PSPP share") and at country level ("Country PSPP share"). We additionally control for the time and cross-sectional variation in scarcity associated to bond holdings by price insensitive ('buy-and-hold') investors ("Bond insensitive share") over the subsample 2014-2018.

On the whole, country-level scarcity appears to create a stronger impact on repo specialness than scarcity at bond-individual level, with this country level impact displaying visible threshold effects (Figure 10 and 11). Sizeable increases in specialness premia are visible once a threshold of PSPP (country) holding shares exceed 10% for French collateral and around 15% for German collateral. In the panel regressions we control for this feature by including a dummy ("Large PSPP share") when PSPP holdings exceed 10% of the total outstanding amount in a given country. We also note that the strength of the PSPP-induced scarcity effect appears to increase with the share of outstanding bonds already held by long-term investors (see Figure 12).

Partial dependence plots suggest a discrepancy in scarcity effects at bond-specific relative to country-specific level. For example, a 15% share of country holdings would correspond to a 10 bps bond specialness premium, while such a holding share of a specific bond would only correspond to a 1-$1\frac{1}{2}$ bp premium. While still present when restricting the sample to 2014-2018 (allowing us to take buy-and-hold investments into account) this discrepancy is estimated to be less pronounced on average, as evident from the panel regressions. For example, panel regressions would attribute an increase in the German specialness premium of broadly 0.3-0.4 bp to one percentage point increase in holding shares both at country or at bond level (for German collateral, see Table 8).

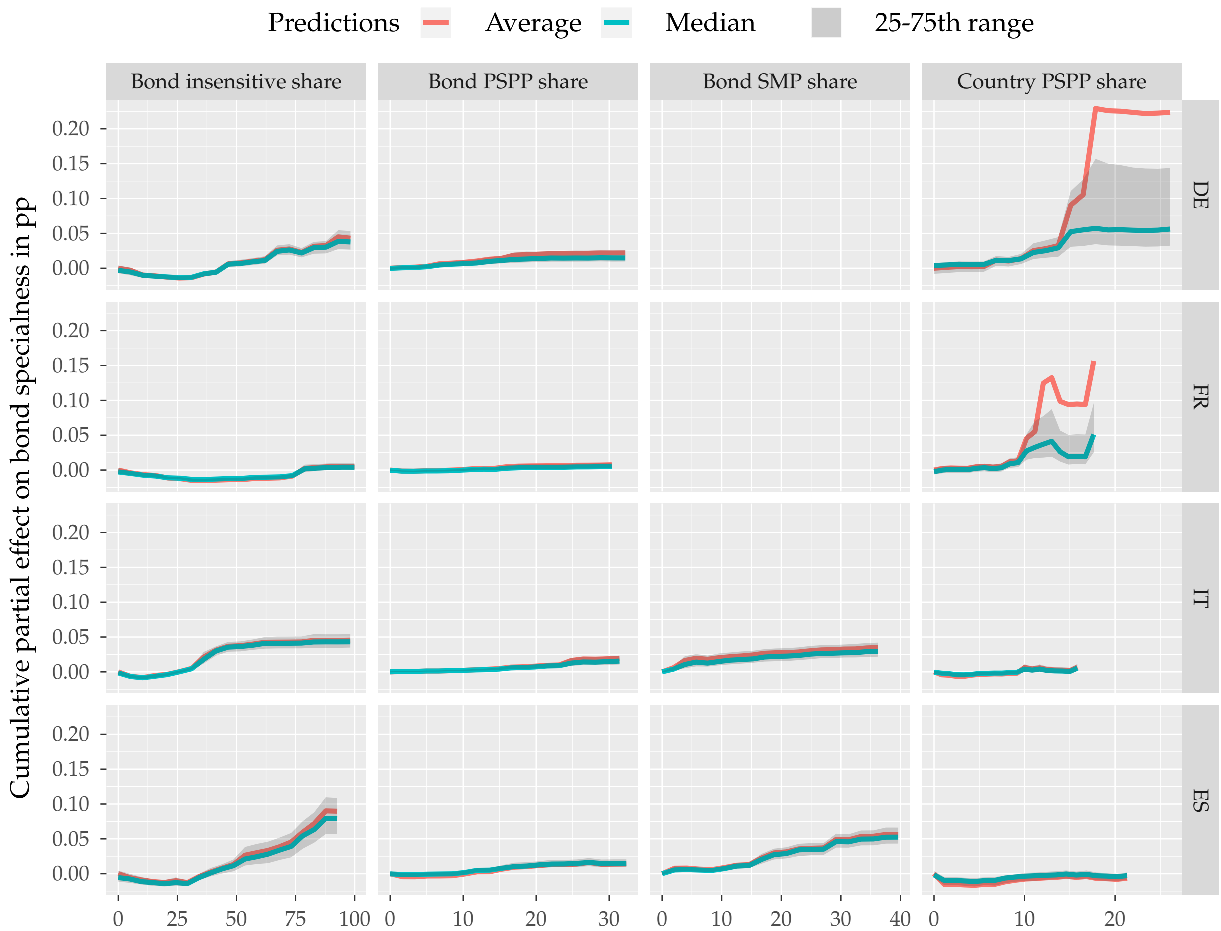
Across models and approaches the French segment exhibits the lowest *bond-level* scarcity effect (even negative effects in most of the panel regressions), while the coefficient estimates associated to the country-level proxy of scarcity are particularly high. A possible explanation is that bond-level PSPP shares of Eurosystem holdings of French bonds are very concentrated around the mean, causing strong correlation between country-level and bond-level holding shares.

Our estimates compare with estimated 0.78 bp increases in special rates, for each percentage point increase in PSPP shares, as reported by Arrata *et al.* (2017), using a different set of covariates, a different panel econometric methodology, and averaging effects out across countries.

PSPP is also relevant for explaining the composite premium on German and French collateral. While the estimated effects of bond-specific holdings are comparable, for the composite premium the country effect is estimated to be only slightly higher (only around 2 bps at 20% holdings in Figure 11) than for the bond specialness premium. This marginal estimated increase in impact is insufficient to explain the widening repo *country* premium (the difference between the composite and the bond specialness premia).

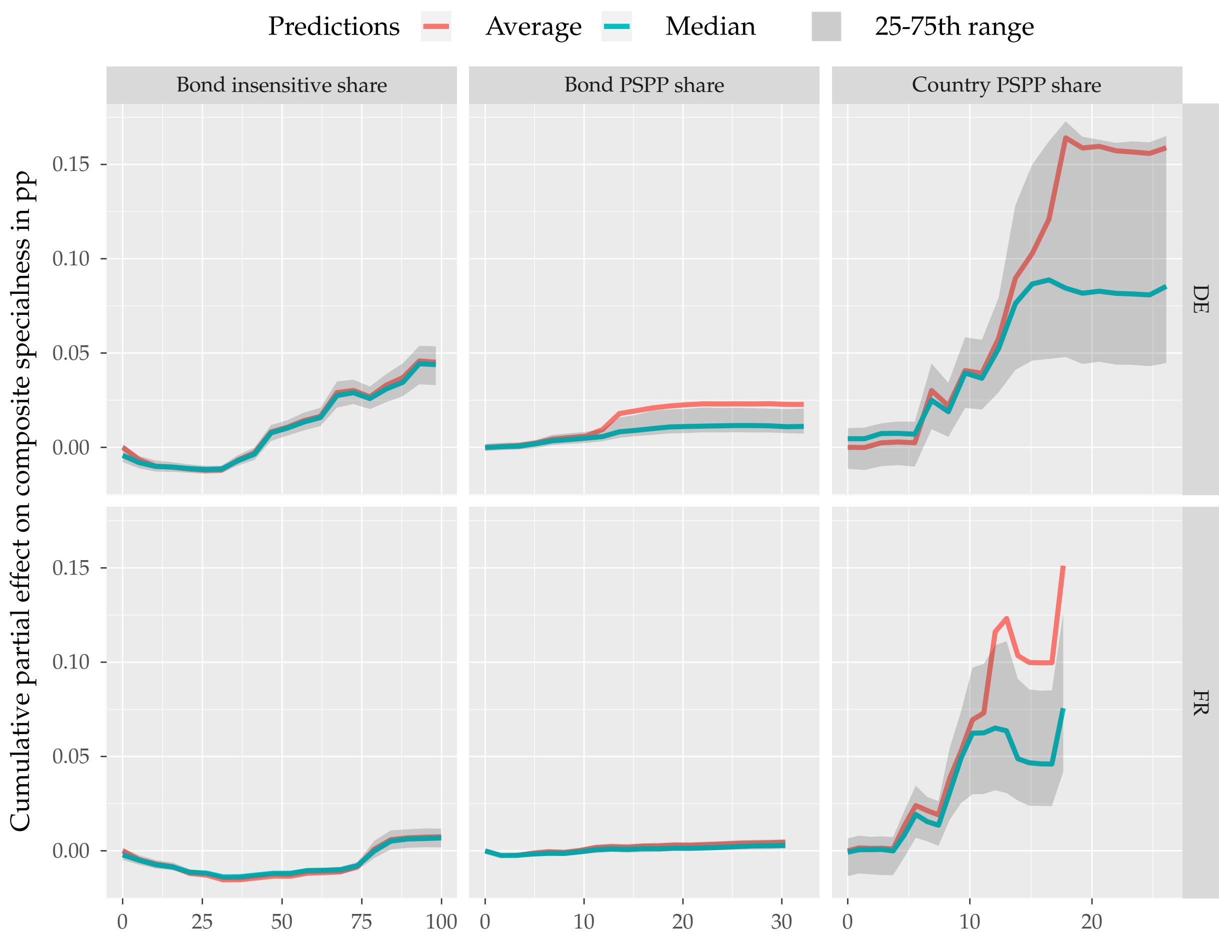
The figures in Section 2.3 showed that, as of January 2017, the upward trend in bond specialness has attenuated, despite further increases in PSPP holdings – a development that coincided with the enhancement of the Eurosystem Securities Lending facility. This flatlining is also visible in the partial dependence plots in Figures 10 and 11 once holding shares approach 20%. The panel regressions account for this effect by interacting PSPP holdings at country level ("Country PSPP share") with a time variable capturing the enhancement ("SecLend enhancement" – entering with a negative sign). Yet, other time-effects, such as market adjustment to the new costly bond sourcing environment or the increase in the supply of bonds from long-term investors (attracted by high returns), have likely contributed to this flatlining in repo premia observed since 2017 as well.

Figure 10: Partial dependence plots for the effects of asset scarcity proxies on bond specialness



Note: Horizontal axes: Bond insensitive share expressed in %, Bond PSPP share in %, Bond SMP share in %, Country PSPP share in %.
Partial dependence predictions are presented for the average tree (the forest) and for the trees corresponding to the first, second, and the third quartiles.

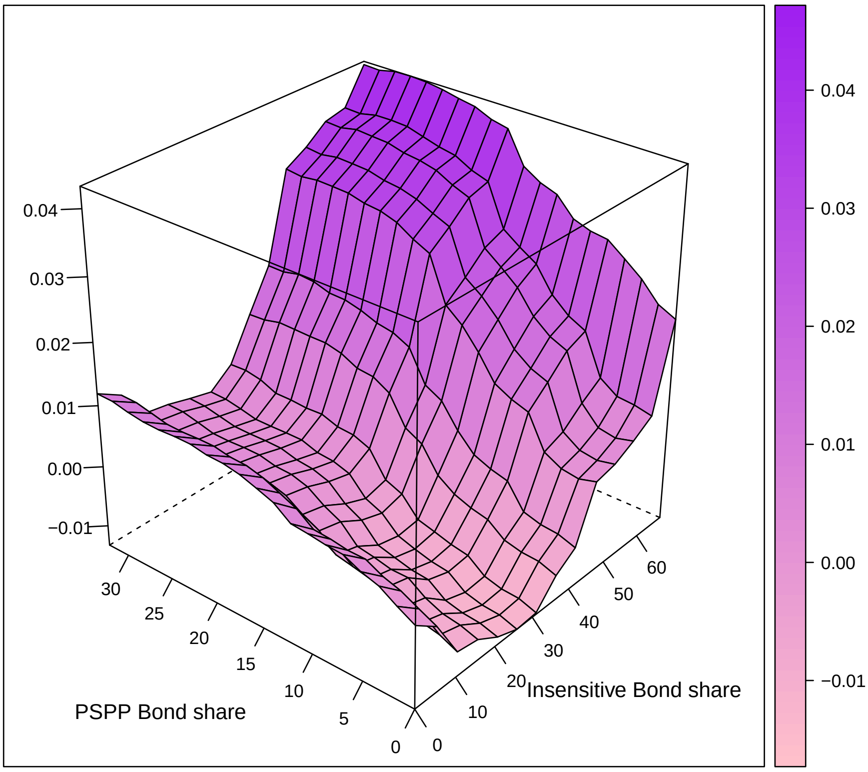
Figure 11: Partial dependence plots for the effects of asset scarcity proxies on composite specialness



Note: Horizontal axes: Bond insensitive share expressed in %, Bond PSPP share in %, Country PSPP share in %. Partial dependence predictions are presented for the average tree (the forest) and for the trees corresponding to the first, second, and the third quartiles.

The scarcity induced by PSPP has generally strengthened the impact of bond-specific features on specialness. According to the panel regressions, German and French on-the-run bonds exhibit higher specialness for a higher level of PSPP holdings. Likewise, specialness of CTD bonds has been increasing with PSPP holdings too, especially in the German segment for which the futures market is the most developed (see Figure 13). Again, we see this impact being attenuated as PSPP holding shares grow beyond 20%.

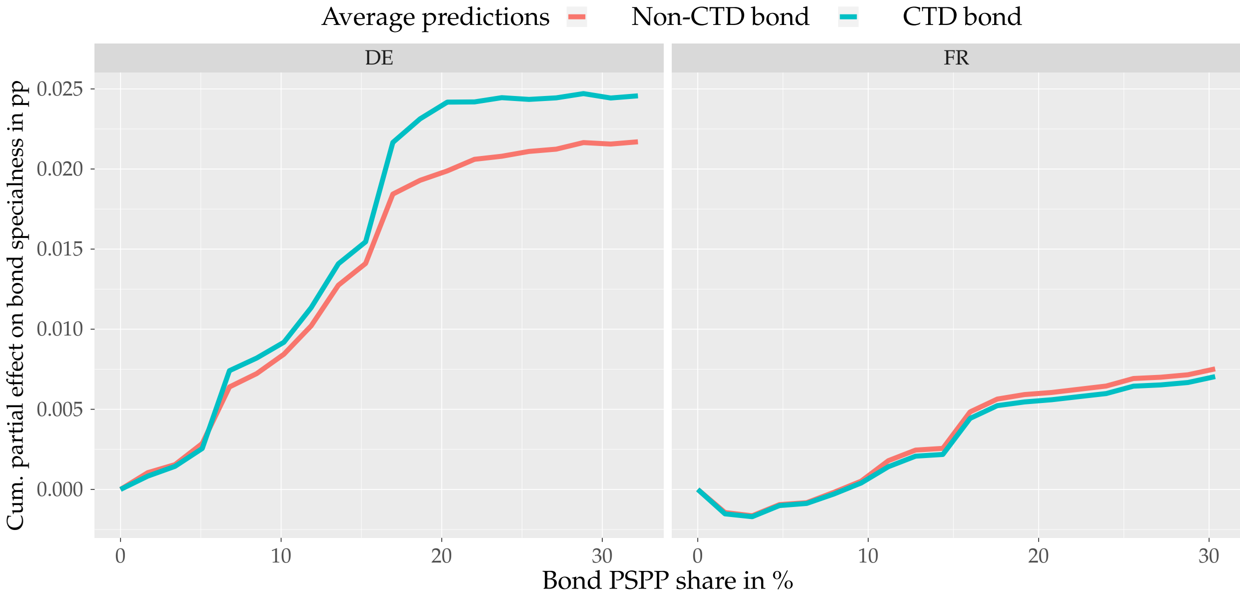
Figure 12: Partial dependence plots for the interacted effect of central bank purchases and holdings of insensitive investors on bond specialness



Note: Partial dependence predictions are presented for the average tree (the forest) and are normalised to zero at origin; X- and y-axes: PSPP bond share and Insensitive share are computed in % of outstanding amount. Z-axis: Cumulative partial effect on bond specialness in pp.

Finally, for completeness, we note a positive impact from bond holdings on bond specialness also for the Securities Market Programme for Italian and Spanish bonds ("Bond SMP share" in Figure 10 and Table 7) validating the findings by Corradin and Maddaloni (2017) on Italian bonds specialness during the SMP period.

Figure 13: Partial dependence plots for the interacted effect of central bank purchases and futures market on bond specialness



Note: Partial dependence predictions are presented for the average tree (the forest) and are normalised to zero to show interactions; Horizontal axes: PSPP bond share is computed in % of outstanding amount.

4 Assessment and outlook

We have provided a comprehensive picture of the impact of structural drivers and the role of financial stress and unconventional monetary policies in the shift from cash- to securities driven money markets since 2010. We document a prevalence of specialness premia being driven by the cash side until the launch of the ECB's 3-year LTROs, with funding risk playing an important role. We estimate that funding stress as experienced during the years 2010-11 has caused a wedge between special rates and the country-specific GC rate of around 5-15 basis points. Subsequently stress and reversals in bond markets can be shown to have driven the securities side of repo transactions. Finally, bond purchases under the PSPP have driven a systematic wedge between SC and GC repo rates, but this effect appears to have been attenuated by enhancements to the Eurosystems Securities Lending Programme and by markets adjusting to asset scarcity (Jank and Mönch (2018)). Overall, we find evidence of PSPP operating through a country-, on top of bond-specific scarcity channel, as also reflected by an increasing safe-asset scarcity spread (of GC repo rates on German and French collateral over GC repo rates on Italian and Spanish collateral). These effects are estimated to have a systematic impact of around 10-20 basis points on the composite specialness premium on French and German collateral.

Our comprehensive approach complements existing literature focusing on specific market segments (Corradin and Maddaloni (2017) for the Italian segment during SMP implementation) or subperiods (Arrata *et al.* (2017) for the period since the inception of PSPP and Ferrari, Guagliano and Mazzacurati (2017) over the period 2013-2015 with a focus on collateral reuse). We validate the importance of the scarcity channel in transmitting central bank purchase programmes, but add robust evidence on the role of bond market reversals and funding stress and a comprehensive set of controls for bond-specific characteristics. Our results point to important asymmetries and non-linearities in how these effects have been transmitted across countries.

At bond-specific level we show that it is important to control for effects on specialness through bond-auctionning cycles and in relation to the futures market. These benchmark features contrast with different characteristics reported for US bond and securities lending markets. We illustrate a structural dominance of the German futures market in driving specialness of bonds.

Our findings are relevant in understanding the evolution in interest rate spreads across different money market segments, both when looking back as well as looking ahead. While in recent years the ECB's asset purchases have been the main driver of repo premia, the asymmetries in repo premia developments across countries also indicate lingering market fragmentation along jurisdictions and a structural scarcity of safe assets. These asymmetries may be perpetuated by more permanent adjustments in market structures and the phasing in of Basel III regulation. In light of these challenges central bank balance sheet normalisation, in whatever guise, might well be insufficient for repo spreads – including GC repo spreads across countries – to revert to pre-crisis levels.

References

Arrata, William, Benoît Nguyen, Imène Rahmouni-Rousseau and Miklos Vari (2017): "Eurosystem's Asset Purchases and Money Market Rates," *Banque de France Working Paper*, (WP#652). Available from: https://publications.banque-france.fr/sites/default/files/medias/documents/document-de-travail-652_2017-11_0.pdf.

Athey, Susan (2018): "The Impact of Machine Learning on Economics," in *The Economics of Artificial Intelligence: An Agenda*, National Bureau of Economic Research, Inc. Available from: https://EconPapers.repec.org/RePEc:nbr:nberch:14009.

Bloomberg (2016): *"Europe's Collateral Crunch,"* Available from: https://www.bloomberg.com/gadfly/articles/2016-11-28/europe-is-at-risk-of-a-collateral-crunch-the-ecb-may-be-too-late.

Breiman, Leo (2001): "Random Forests," *Machine Learning*, **45**(1), 5–32. Available from: https://link.springer.com/article/10.1023/A:1010933404324.

Breiman, Leo, Jerome H. Friedman, Richard A. Olshen and Charles J. Stone (1984): *Classification and regression trees*, Brooks/Cole publishing.

Bucalossi, Annalisa and Antonio Scalia (2016): "Leverage ratio, central bank operations and repo market," *Questioni di Economia e Finanza (Occasional Papers)*. Available from: https://www.bancaditalia.it/pubblicazioni/qef/2016-0347/QEF_347_16.pdf.

Buraschi, Andrea and Davide Menini (2002): "Liquidity risk and specialness," *Journal of Financial Economics*, **64**(2), 243–284.

CGFS (2017): "Repo market functioning," *Bank for International Settlements Report*, **59**.

Corradin, Stefano and Angela Maddaloni (2017): "The importance of being special: repo markets during the crisis," *ECB Working Paper Series*, (No 2065). Available from: https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2065.en.pdf.

D'Amico, Stefania, Roger Fan and Yuriy Kitsul (2014): "The scarcity value of Treasury collateral: Repo market effects of security-specific supply and demand factors," *Finance and Economics Discussion Series 2014-60*, (2014-60).

Duffee, Gregory R. (1996): "Idiosyncratic Variation of Treasury Bill Yields," *The Journal of Finance*, **51**(2), 527–551. Available from: https://www.jstor.org/stable/2329370.

Duffie, Darrell (1996): "Special Repo Rates," *The Journal of Finance*, **51**(2), 493–526. Available from: http://www.jstor.org/stable/2329369.

Duffie, Darrell and Arvind Krishnamurthy (2016): "Passthrough efficiency in the Fed's new monetary policy setting," in *Kansas City Federal Reserve Symposium on Designing Resilient Monetary Policy Frameworks for the Future*, Federal Reserve Bank of Kansas City, 1815–1847. Available from: https://www.gsb.stanford.edu/sites/gsb/files/publication-pdf/jh-september-8-2016-bw.pdf.

Ejsing, Jacob and Jukka Sihvonen (2009): "Liquidity premia in German government bonds," *ECB Working Paper Series*, (No 1081). Available from: https://www.ecb.europa.eu/pub/pdf/scpwps/ecbwp1081.pdf?ae81b6fa5af3f3e276eaa7308c665dad.

Ferrari, Massimo, Claudia Guagliano and Julien Mazzacurati (2017): "Collateral scarcity premia in euro area repo markets," *ESRB Working Paper Series*, (No 55). Available from: http://www.esrb.europa.eu/pub/pdf/wp/esrb.wp55.en.pdf.

Fisher, Mark (2002): "Special Repo Rates: An Introduction," *Economic Review*, **Vol. 87**(No. 2). Available from: https://www.frbatlanta.org:443/research/publications/economic-review/2002/q2/vol87no2_special-repo-rates.

Friedman, Jerome, Trevor Hastie and Robert Tibshirani (2001): *The elements of statistical learning*, Volume 1, Springer series in statistics New York.

Friedman, Jerome H. (2001): "Greedy function approximation: a gradient boosting machine," *Annals of statistics*, 1189–1232.

Huh, Yesol and Sebastian Infante (2017): "Bond Market Intermediation and the Role of Repo," *Finance and Economics Discussion Series 2017-003*, (2017-003). Available from: https://doi.org/10.17016/FEDS.2017.003.

James, Gareth, Daniela Witten, Trevor Hastie and Robert Tibshirani (2014): *An Introduction to Statistical Learning with Applications in R*, Springer New York.

Jank, Stephan and Emanuel Mönch (2018): "Safe Asset Shortage and Collateral Velocity," *Deutsche Bundesbank internal memo*.

Mancini, Loriano, Angelo Ranaldo and Jan Wrampelmeyer (2016): "The euro interbank repo market," *The Review of Financial Studies*, **29**(7), 1747–1779. Available from: https://doi.org/10.1093/rfs/hhv056.

Sirignano, Justin, Apaar Sadhwani and Kay Giesecke (2018): "Deep Learning for Mortgage Risk," Available from: https://papers.ssrn.com/abstract=2799443.

Upper, Christian and Thomas Werner (2007): "The tail wags the dog: time-varying information shares in the Bund market," *BIS Working Papers*, (No 224). Available from: https://www.bis.org/publ/work224.pdf.

Varian, Hal R. (2014): "Big Data: New Tricks for Econometrics," *Journal of Economic Perspectives*, **28**(2), 3–28. Available from: https://pubs.aeaweb.org/doi/pdfplus/10.1257/jep.28.2.3.

A Specialness premia and bond-market specific features

Bond-market specific features affect the securities-driven side of the repo market. Such features relate to benchmark characteristics arising from bond-auctionning cycles and deliverability into futures, and, in particular, from a bond being CTD. Ejsing and Sihvonen (2009) have documented that benchmark status is strongly concentrated in bonds deliverable into futures, especially in jurisdictions where the size of the future market is high relative to the bond market. Table 4 depicts the size of the futures market relative to the bond market for our countries of interest. Consistent with the findings in Ejsing and Sihvonen (2009) the relative size of the German futures market stands out relative to the other countries. The German futures market is about 60 times larger than the amount of outstanding debt and 13 times larger than the volume of the bond market. In France, the futures market is about the size of the bond market, in Spain the relative size is only marginal.

Table 4: The market for government securities and related futures (2010-2017)

	Amount outstanding (€ bn)*	Bond market total volume (€ bn)**	Futures market total volume (€ bn)***	Relative size of futures market in % of cash market
DE	1169	5256	68925	1311%
ES	882	7065	21	0%
FR	1530	3265	3733	114%
IT	1718	1247	3147	252%

Notes: * Average total face value of central government bonds in circulation (computed on the basis of end-of-year snapshots from 2010 to 2017).
** Average value of future contracts exchanged over a one-year period (average on the period 2010-2017).
*** Average of yearly turnover in the secondary market for government securities (average on the period 2010-2017).
Source: Eurex, ECB, Deutsche Finanzagentur, Banca d'Italia, Banco de España, Agence France Trésor.

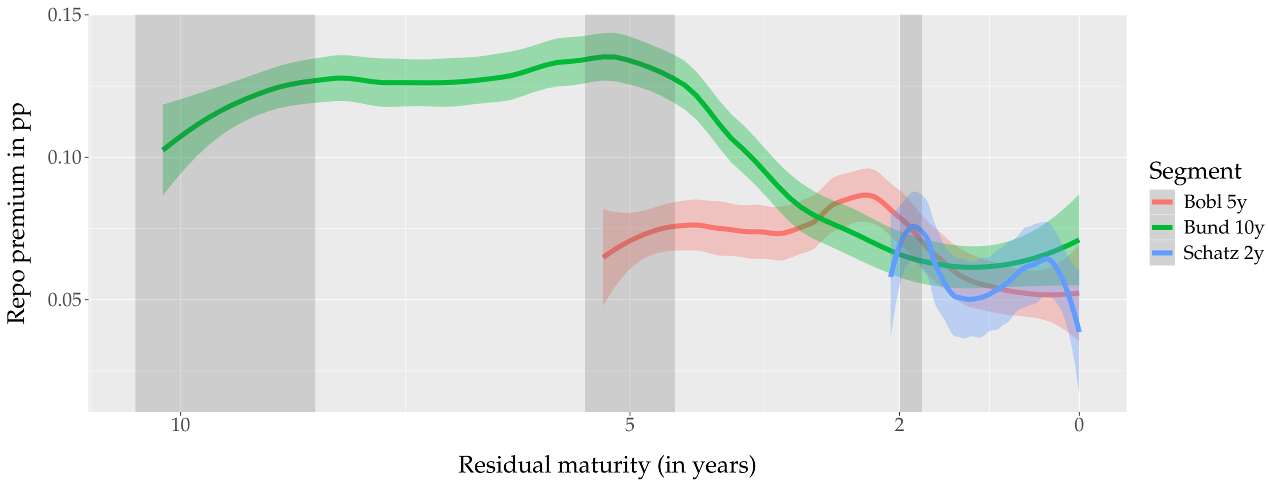
Figure 14 illustrates, for the German segment, the interrelation of deliverability into futures and the bond specialness premium over the life of the 2 year Schatz, the 5 year Bobl, and the 10 year Bund.[11] Dark shaded areas indicate the periods in which such bonds are deliverable in the futures market. Within these periods bond specialness is higher, reflecting higher liquidity or benchmark status of the underlying instrument.

Figure 15 displays bond specialness around delivery dates, showing that peaks around those dates are highest for CTD bonds.[12] The Spanish market segment does not match this pattern which is likely due to the shallowness of its futures market (reported in Table 4).

[11] In this section all charts depicting repo premia refer to the bond specialness premium as defined in the introduction (see Annex B for detailed explanations on the calculation of such premium). The bond specialness premium is here taken as example, but composite specialness premium exhibit the same features.

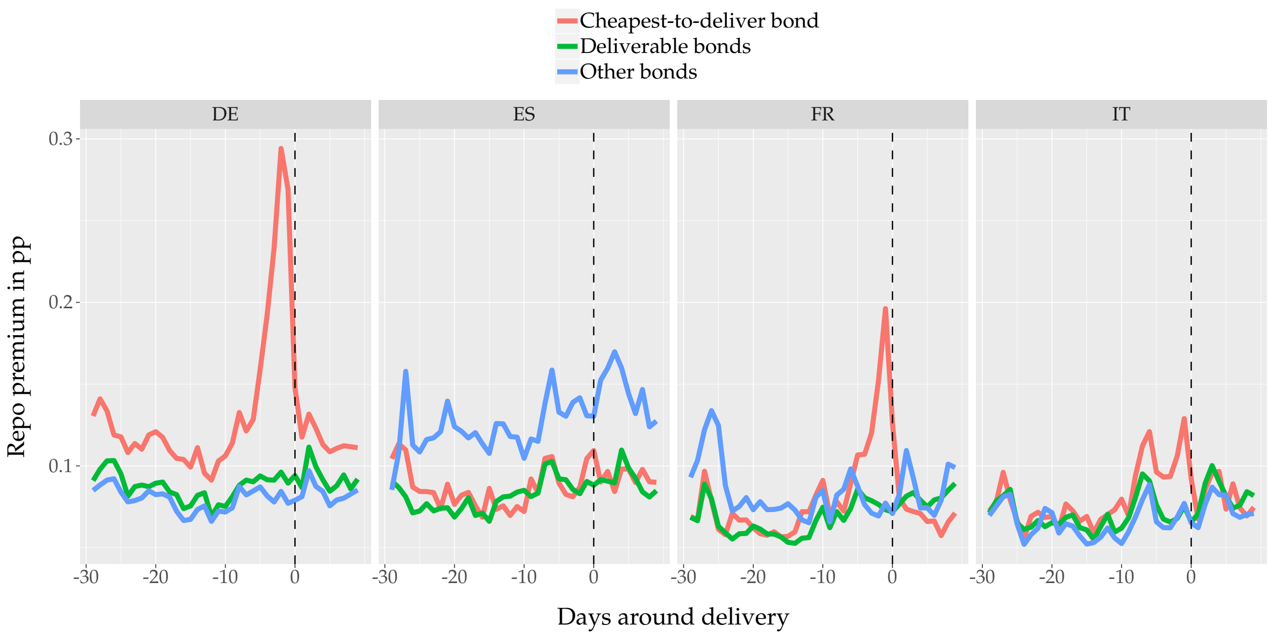
[12] Delivery into bond futures can be fulfilled by delivering any bond from a given basket. Delivery values of bonds are calculated by bond-specific conversion factors. These delivery values diverge due to the effect of yield curve movements on the fixed conversion factors and, as a result, one bond will be cheapest-to-deliver (CTD).

Figure 14: Specialness premia and benchmark characteristics over the life of German bonds



Note: Bond specialness premium as a function of its residual maturity. Shaded areas indicate the periods during which these bonds are deliverable into German futures contracts. The lines are averages of bond specialness premia among all bonds within the same segment and are fitted LOESS curves.
Source: BrokerTec, MTS.

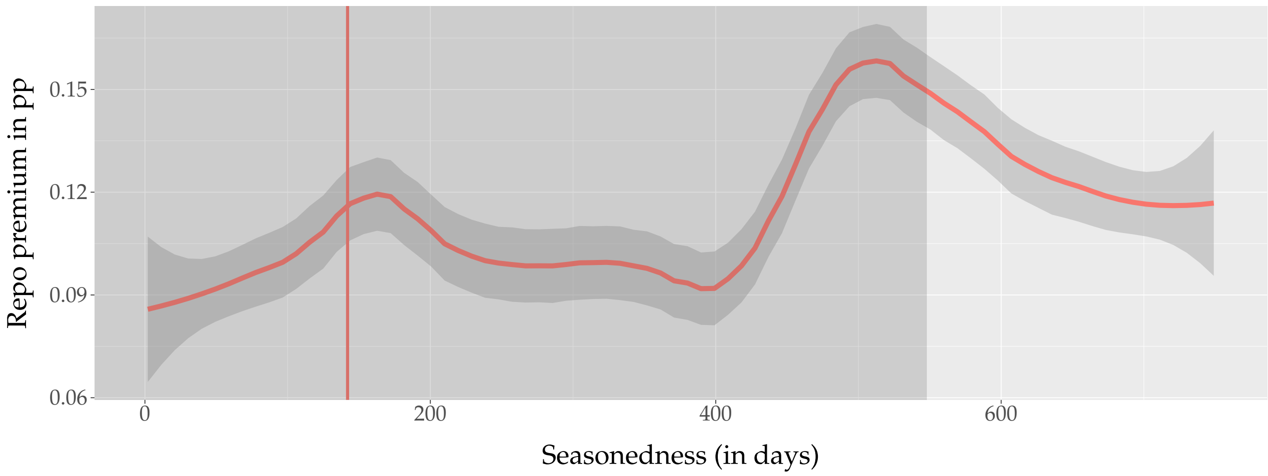
Figure 15: Repo specialness premia around futures delivery date



Note: The repo premium for CTD and deliverable bonds is first averaged by day around delivery and future contracts and, subsequently, by country. The dashed black line represents the delivery date.
Source: BrokerTec, MTS.

Figure 16 displays bond specialness of a 10-year Bund in relation to its seasonedness, with the grey-shaded area showing the period of deliverability in the futures market and the solid vertical line indicating the average time before a new bond of the same maturity is issued – i.e. when the original one goes off-the-run. There are two peaks in bond specialness, the first before the bond goes off-the-run and the second just before the bond loses eligibility to be delivered into futures.

Figure 16: Bond specialness premia and on-the-run and deliverability features for the 10-year Bund

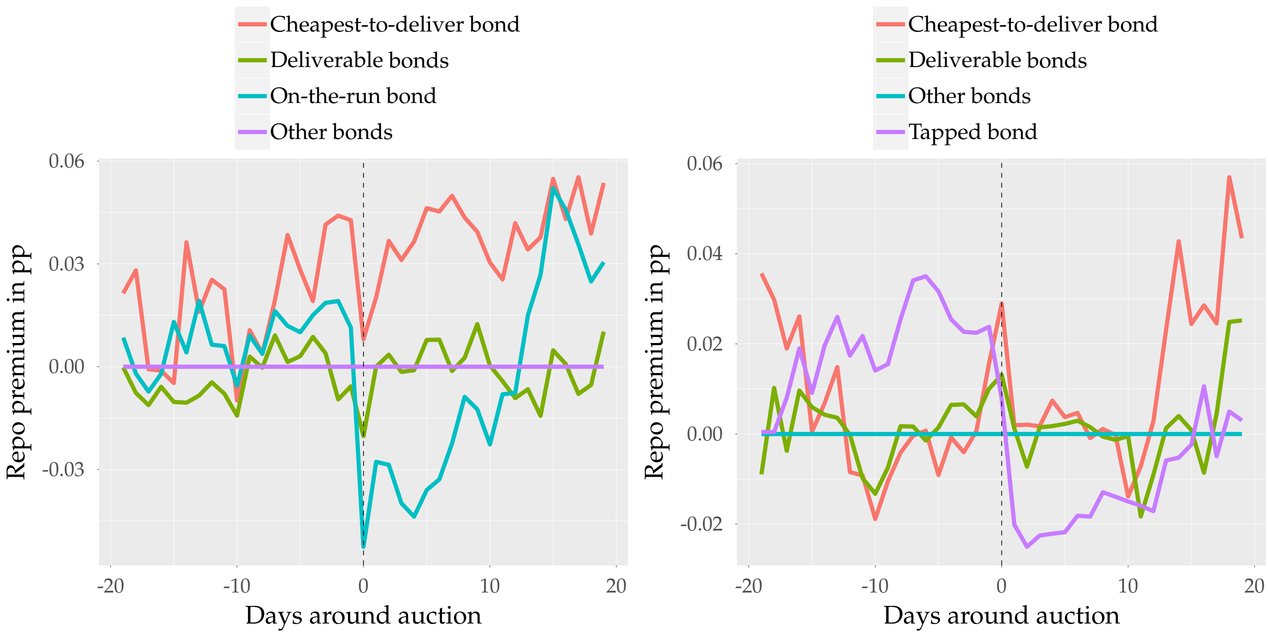


Note: Bond specialness premium of a 10-year Bund over its life cycle. Seasonedness is a variable counting the number of business days that have elapsed since the day of bond issuance. Shaded areas present the period during which these bonds are deliverable into Eurex Euro-Bund Futures. The line is a fitted LOESS curve with 95%-confidence bands. The solid red vertical line shows the average number of days before a new bond is issued and the current on-the-run bond goes off-the-run.
Source: BrokerTec, MTS.

Figures 17a and 17b show the link between bond-auctionning cycles (around issuance and tapping dates) and repo specialness, considering different bond characteristics (for German and Italian collateral, respectively). We can discern that specialness trends higher towards issuance and tapping dates and subsequently sags. In particular, the newly issued bond (which acquires the on-the-run status) trades significantly less special with respect to all other bonds and, similarly, repo specialness on tapped bonds drops significantly after tapping. This dip in specialness in the on-the-run and tapped bonds, respectively after issuance and tapping, is reversed later on as these bonds re-gain liquidity.

This pattern over the issuance cycle likely results from market makers requiring repo to hedge intervals between buying and selling. Thereby market makers borrow cash using a non-benchmark bond to fund the new bond issue and reverse in the benchmark (on-the-run) bond to short-hedge market risk for the new issue (see Huh and Infante (2017)'s theoretical modelling of how repos allow dealers to finance their activities and their ability to satisfy levered client demands when having to adjust their holdings of risky assets). On the bond issuance day market makers bid for the new bond to deliver to investors and sell off the meanwhile 'old' (off-the-run) benchmark bond. For an exposition of the relationship between bond liquidity premia and bond specialness premia over bond-auctionning cycles for the US, see Fisher (2002) and for a discussion of such effects in the German Bund market Upper and Werner (2007) and especially Ejsing and Sihvonen (2009).

Figure 17: Bond specialness premia over bond-auctionning cycles



(a) German issuance premium

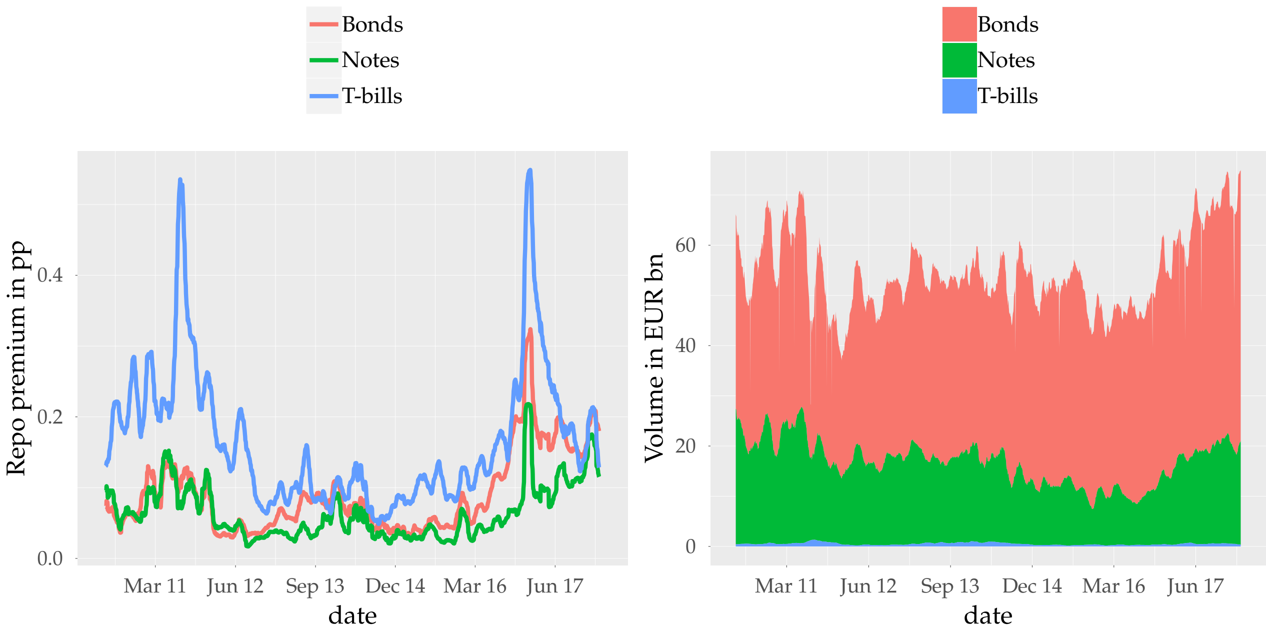
(b) Italian tapping premium

Note: The figure on the left-hand side shows the bond specialness premium around the issuance dates for German bonds, while the one on the right-hand side shows the bond specialness premium around tapping dates for Italian bonds. Indeed, effects from bond issuance and tapping are particularly visible for these countries. Specialness is presented in deviation from the specialness of "Other bonds". The dashed lines in both figures correspond to the issuance date of the new bond or the tapping date of an already existing bond.
Source: BrokerTec, MTS.

Figure 18a illustrates that, for the German market, Treasury bills, despite playing only a marginal role in terms of repo-turnover volumes (see Figure 18b), systematically exhibit a higher specialness premium than any other bond. The difference in specialness between Treasury bills and other bonds likely reflects their peculiarity in terms of liquidity and safety in the cash market (see Duffee, 1996, who relates this 'convenience yield' feature to market segmentation). Moreover, since the inception of PSPP in 2015, specialness on these bonds (which have not been eligible for purchase), has gone up in tandem with those of purchased bonds (of higher maturity). The structural concentration of high specialness on Treasury bills, especially during changing tides of the monetary policy cycle, is likely owing to these instruments being predominantly used to hedge against or speculate on policy rate changes, as also emphasised previously by Duffie (1996). During the period 2010-2012 this feature obviously seems more relevant than for the period since 2015 where, under the Asset Purchase Programme (APP) and forward guidance, monetary policy increasingly operated through lowering term premia at long maturities.[13]

[13]The rise in specialness premia in Treasuries in the latter period may be owing to indirect effects from APP: counterparties without access to the ECB's deposit facility could have used Treasury bills for investing the liquidity received from selling bonds under PSPP into safe and liquid securities (close substitutes for cash). Yet specialness premia on Treasuries have co-moved with that in bonds, reflecting the importance of country-specific scarcity effects, on top of ISIN-specific ones.

Figure 18: German bond specialness premia and trading volumes by bond types



(a) Bond specialness premium by bond type

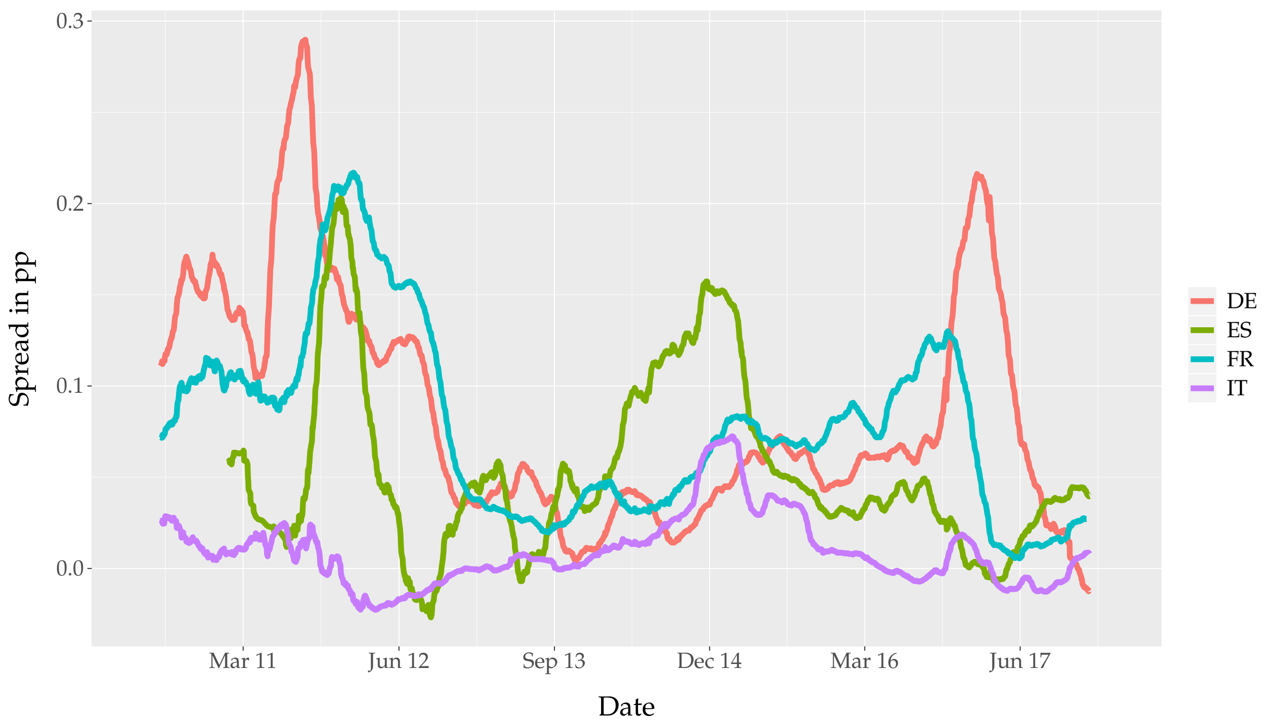
(b) SC volumes by bond type

Note: Specialness premium and volumes are summarised with 30-days centered rolling-average.
Source: BrokerTec, MTS.

Figure 19 presents the difference between bond specialness of Treasury bills and the mean specialness of other bonds for our four countries of interest.[14] While the level of specialness is structurally higher on Treasury bills (the spread in the chart is constantly above zero) for all jurisdictions, it is especially the case for countries considered as providers of 'safer assets' (Germany and France) and in general more persistent over the funding and sovereign crisis periods as well as during the implementation of PSPP.

[14]Here we distinguish three main types of bonds characterised by their initial maturity and auction characteristics: T-bills, Notes and Bonds (see Table 5 in Annex B.3). Inflation-linked bonds and other bonds are not included in Figure 19. In our subsequent analyses, we are using a more comprehensive set of bonds categorised in more granular terms.

Figure 19: Specialness premia on T-Bills over other bonds



Note: Specialness premium is summarised with 90-days centered rolling-average.
Source: BrokerTec, MTS.

B Data collection and aggregation

B.1 Dependent variables: Repo premia

Our study focused on repo transactions with one day of maturity and backed by sovereign bond collaterals. We were interested on transactions with the following settlement structure: Overnight (T+0), Tomorrow-Next (T+1), Spot-Next (T+2). All General Collateral (GC) and Special Collateral (SC) repo transactions used in the analysis have been obtained from the records of the BrokerTec and the MTS repo platforms and we have only included those which have been cleared through a Central Counterparty Clearing house (CCP) to exclude counterparty risk in the pricing. Our dataset covers all German, French, Spanish and Italian collaterals lent in the European repo market over the period 1 May 2010 - 28 February 2018.

In order to construct the measure of *bond specialness premium*, we followed the methodology proposed by Corradin and Maddaloni (2017): we have matched all SC transactions with the "closest-in-time" country-specific GC transaction, no matter whether the latter has occurred before or after the former. The matching is country-specific since for instance a repo SC trade on a specific bond German cannot be matched with a GC trade on Italian or French bonds. Two transactions are considered the "closest in time" based on the number of seconds that have elapsed between them (according to the records). If two GC transactions on the same country collateral occurred in the same second, we apply a volume-weighted average on the rates. The same GC transaction could be matched with several SC ones provided that it is the closest. We applied the constraint that the matched GC and SC transactions should have occurred on the same trading day.

Following the matching, we computed the spread between intraday GC and SC rates and we have calculated, for every single collateral in our dataset (i.e. each ISIN), the daily volume-weighted average of these GC-SC spreads. We cleaned for all observations for which the bond specialness premium is negative or equal to zero as we consider them too much affected by poor intraday matching and/or high intraday variability. The weights used are the relative trading volumes associated to the special transactions. The resulting ISIN-level spread is referred to as the bond specialness premium. We further drop the upper 2% of the dataset according to the bond specialness premium in order to control for outliers in the data.

The *composite specialness premium* has instead been constructed as simple spread between the time series of the GC Pooling ECB EXTended repo rate on overnight transactions (O-N) provided by Eurex and the ISIN-specific SC rates which have been computed on the basis of the transactions in BrokerTec and MTS. Both rates are daily volume-weighted averages of the intraday rates. Mirroring the cleaning procedure applied for constructing the bond specialness premium, we drop negative premia and the upper 2% of the observations.

B.2 Explanatory variables

Explanatory variables capturing bank funding stress:

- Total MRO stock: Aggregate stock of main refinancing operations recorded on the Eurosystem balance sheet at the end of the day.
- Total LTRO: Aggregate stock of long-term financing operations recorded on the Eurosystem balance sheet at the end of the day.
- Total 6M LTRO: Aggregate stock of 6-months long-term financing operations recorded on the Eurosystem balance sheet at the end of the day.
- Total 1Y LTRO: Aggregate stock of 12-months long-term financing operations recorded on the Eurosystem balance sheet at the end of the day.
- Total 3Y LTRO: Aggregate stock of three-years long-term financing operations recorded on the Eurosystem balance sheet at the end of the day.

- Excess liquidity: Level of excess liquidity at the end of the day computed on the basis of the following Eurosystem balance sheet items: Excess Liquidity = Current Account + Deposit Facility Recourse - Minimum Reserve Requirements.
- Euribor-OIS: Spread between the 3-month Euribor and the 3-month OIS rate, generally considered as a good measure for stress in unsecured markets.

Other factors which have been relevant during the period of funding stress are captured by:

- Euro collateral pool, for each bond, is the ratio of the nominal amount (relative to outstanding) which has been pledged as collateral in Eurosystem refinancing operations. This ratio highly correlates with the size of refinancing operations over time and captures their potential indirect impact on asset scarcity in certain category of bonds.
- Interest rate reversals are proxied by the 15-days moving average of absolute changes in the OIS 3-months rate in 3-months. This measure captures specific periods in which there are significant changes in future short-term rate expectations. Hedging against interest rate risk is typically done by investing in specific category of bonds which in turn would show higher specialness premia during periods of interest rate reversals.

Explanatory variables capturing sovereign credit risk:

- Flight-to-safety: Maturity-specific first principle component of Italian and Spanish sovereign yield spreads to the corresponding jurisdiction. This variable, by construction, exists only in the model specifications for German and French bonds and it is supposed to control for flight-to-safety phenomena from non-core jurisdictions' bonds to core-jurisdictions' bonds.
- Yield spread: Maturity-specific sovereign yield of the corresponding jurisdiction to Germany; equal to zero for Germany by construction.
- Yield curve spread-Level: First principle component of the sovereign yield spread curve of the corresponding jurisdiction to Germany; equal to zero for Germany by construction.
- Yield curve spread-Slope: Second principle component of the sovereign yield spread curve of the corresponding jurisdiction to Germany; equal to zero for Germany by construction. It corresponds to a measure of the slope of the credit spread. The steepness (downward) slope reflects a higher level of sovereign risk.

Explanatory variables capturing safe asset scarcity:

- Bond PSPP share, for each bond, constitutes the share of Eurosystem PSPP holdings over the corresponding total marketable outstanding amount, whereby both components of the ratio are expressed in face value terms. It captures the bond-level scarcity implied by the Public Sector Purchase Programme (PSPP).
- Bond SMP share, for each bond, constitutes the share of Eurosystem SMP holdings (of Italian and Spanish bonds) over the corresponding total marketable outstanding amount, whereby both components of the ratio are expressed in face value terms. It captures the bond-level scarcity implied by the Securities Markets Programme (SMP). Obviously, as only Italy and Spain have been affected by this program, this variable is not included in the model specifications of Germany and France
- Country PSPP share, for each country, constitutes the share of Eurosystem PSPP holdings over the corresponding total marketable outstanding amount, where both components of the ratio are expressed in face value terms. It captures the country-level scarcity implied by the Public Sector Purchase Programme (PSPP).
- Bond insensitive share, for each bond, constitutes the share of the amount held by buy-and-hold investors (i.e. price insensitive investors) over the corresponding total marketable outstanding amount, where both components of the ratio are expressed in face value terms. Price-insensitive investors comprise the foreign official sector, euro area insurance companies and pension funds as well as euro area general governments. Eurosystem holdings are excluded from the calculation. Data are from the ECB's Securities Holdings Statistics. The variable controls for asset scarcity of some bonds due to high concentration of them on buy-and-hold investors.

Controls for bond-specific features:

Time-invariant

- Inflation-linked: dummy controlling for inflation-linked bonds.
- Fixed coupon: dummy controlling for bonds being issued with a fixed coupon rate.
- Floating coupon: dummy controlling for bonds being issued with a floating coupon rate.
- Initial maturity: value expressing the years-to-maturity of each bond at issuance. Values are integers, truncated values of the initial maturity expressed in decimals.

Time-variant

- On-the-run: dummy for the latest issued bond among bonds of the same type (e.g. the latest bond issued among all Bund 10 years currently marketable).

- Residual maturity measures the time remaining until the bond matures.
- Modified duration: Macaulay duration divided by its gross yield-to-maturity $(1 + YTM)$. It measures the proportional sensitivity of a bond price to an absolute change of one percent in its yield.
- Deliverable bonds: dummy controlling for bonds which are deliverable into futures contracts.
- CTD: dummy for the bonds, among those deliverables into future markets, which are "cheapest-to-deliver".
- CTD around delivery: dummy for the bonds, among those deliverables into future markets, which are "cheapest-to-deliver" in the last three days before delivery date.

Seasonality and time effects:

- Pre-issuance: dummy variable for the 15 days preceding an issuance.
- Post-issuance: dummy variable for the 15 days following an issuance (including the issuance day).
- Pre-tapping: dummy variable for the 15 days preceding a tapping.
- Post-tapping: dummy variable for the 15 days following a tapping (including the tapping day).
- End-MPs: dummy for the last trading day of each maintenance period of 2012 in order to control for spikes in specialness premia due to bank liquidity management strategies.
- Last-of-quarter: dummy for the last trading day of the quarter.
- End-of-year dummy for the last 4 trading days of the year. Separate dummies for the end-year 2015, 2016 and 2017 are also included in the panel regressions as window dressing phenomena have been particularly significant.
- Time FE: Time fixed effects, i.e. one dummy for each trading day of the sample. These dummies are included in the random forests and in the fixed-effect panel regressions.

Financial markets data have been extracted from Bloomberg, security holdings data by sector from the ECB Securities Holdings Statistics (SHS) and all relevant Eurosystem balance sheet data, including ISIN-specific Eurosystem securities holdings, from ECB internal sources.

B.3 Panel regression controls

Table 5 provides a cross-country overview of the distribution of bond types and their corresponding repo traded volumes in our database. It illustrates the specifics of each government debt management across jurisdictions.

Table 5: Monthly average volume of special repo transactions by segment in € bn

	DE		ES		FR		IT	
T-Bills	*BuBill 6m*	4.5	*Letras 12m*	13.9	*BTF 3m*	9.6	*BOT 6m*	36.0
	BuBill 1y	7.1	*Letras 18m*	2.6	*BTF 6m*	8.6	*BOT 12m*	78.2
					BTF 12m	17.8		
Notes	*Schatz 2y*	130.4	*Bonos 3y*	13.9	*BTAN/OAT 2-3y*	22.5	*CTZ 24m*	50.4
	Bobl 5y	243.7	*Bonos 5y*	33.4	*BTAN/OAT 5y*	106.2	*BTP 3y*	104.2
							CCT 5-7y	60.4
							BTP 5y	171.2
Bonds	*Bund 10y*	734.0	*Bonos 10y*	77.5	*OAT 10y*	229.2	*BTP 7y*	37.0
	Bund 30y	115.3	*Bonos 15y*	23.0	*OAT 15y*	94.7	*BTP 10y*	267.0
			Bonos 30y	20.4	*OAT 20y*	2.8	*BTP 15y*	129.7
			Bonos 50y	0.4	*OAT 30y*	54.5	*BTP 20y*	3.1
					OAT 50y	9.65	*BTP 30y*	91.1
							BTP 50y	0.9
Inflation-Linked		25.9		3.2		49.6		50.1
Others		0.0		0.5		1.2		0.8
TOTAL		**1261**		**189**		**606**		**1080**

Notes: Special repo volumes presented above refer to the monthly average in the sample period considered (May 2010-Feb 2018). "Others" refers to bonds which which have been discontinuously issued over our sample or with distinctive characteristics from other segments. Inflation-Linked bonds have been set apart as they could not be considered perfect substitutes of bonds with similar maturity but fixed coupon rates. Their degree of liquidity in the cash market also typically differs.
Source: BrokerTec, MTS, ECB.

C Data mining tools

C.1 Hierarchical structures and non-linearities

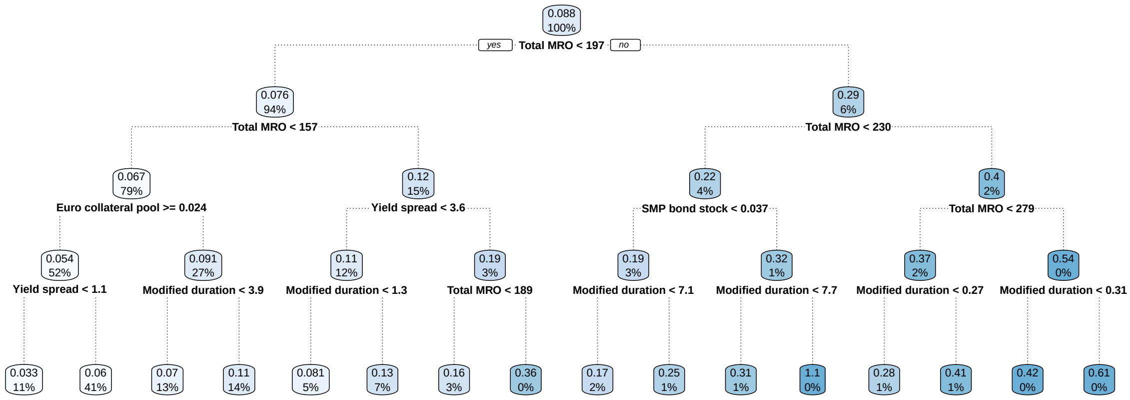
For illustrative purposes, we show two pruned regression trees with bond specialness as dependent variable. We restrict the data to two sub-periods: the pre-PSPP period, from the beginning of the sample to start of PSPP (9 March 2015), and the PSPP period, from the start of PSPP to the end of the sample (28 February 2018). We present the Italian segment and the German segment respectively for the first and second sub-periods, as they represent the countries which carry particularly high bond specialness. Annex C.2 provides more details on the construction of the trees.

The trees are inverted for visualisation with branches and leaves spreading out from the trunk at the top. The splitting rules are best read from bottom to top to understand the segmentation of a particular region. Any final region (terminal node) or intermediate region (intermediate node) represent a cluster of observations which are summarised by their mean and by their share relative to the entire sample.[15] The mean specialness premia at the nodes represent the regression trees' conditional predictions based on our choice for the explanatory variables.

While only representing simplified trees, Figures 20 and 21 reflect a hierarchy across the feature space, threshold effects, and non-linearities. In the pre-PSPP period, our proxies for funding stress (particularly MRO recourse) and sovereign bond market stress are identified as predominant factors. The Securities Market Programme (SMP), to a lesser extent, is also found to be relevant for bond specialness on Italian collateral, especially when the SMP holdings in a specific bond exceed around 4% of its total outstanding amount. Conversely, during the PSPP period, funding stress proxies do not appear high in the tree; measures of country-level and bond-level scarcity, jointly with bond specific characteristics, are dominant factors in explaining bond specialness. A threshold in German bond specialness is identified when total Eurosystem PSPP holdings of German government bonds exceed 13% of total outstanding amount.

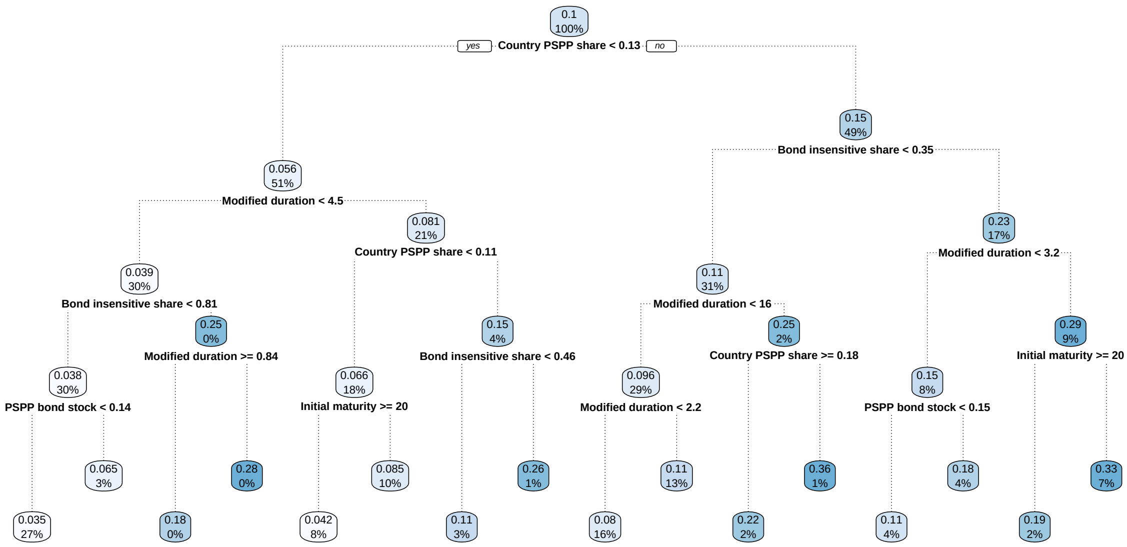
[15] The tree is always constructed in a way that, below each node, the cluster with the highest bond specialness appears on the right-hand side of the tree and that the mathematical condition characterising the splitting is always satisfied on the left-hand side of the tree.

Figure 20: Simplified regression tree for the pre-PSPP period for the Italian Segment



Note: The darker the shade of blue on a box is, the higher the bond specialness premium is in the cluster it summarizes. For visualisation purposes the depth of the trees has been restricted to four. Days subject to seasonal effects (i.e. month-end, quarter-end and year-end) have been removed. We exclude Treasury bills in this example.

Figure 21: Simplified regression tree for the PSPP period for the German Segment

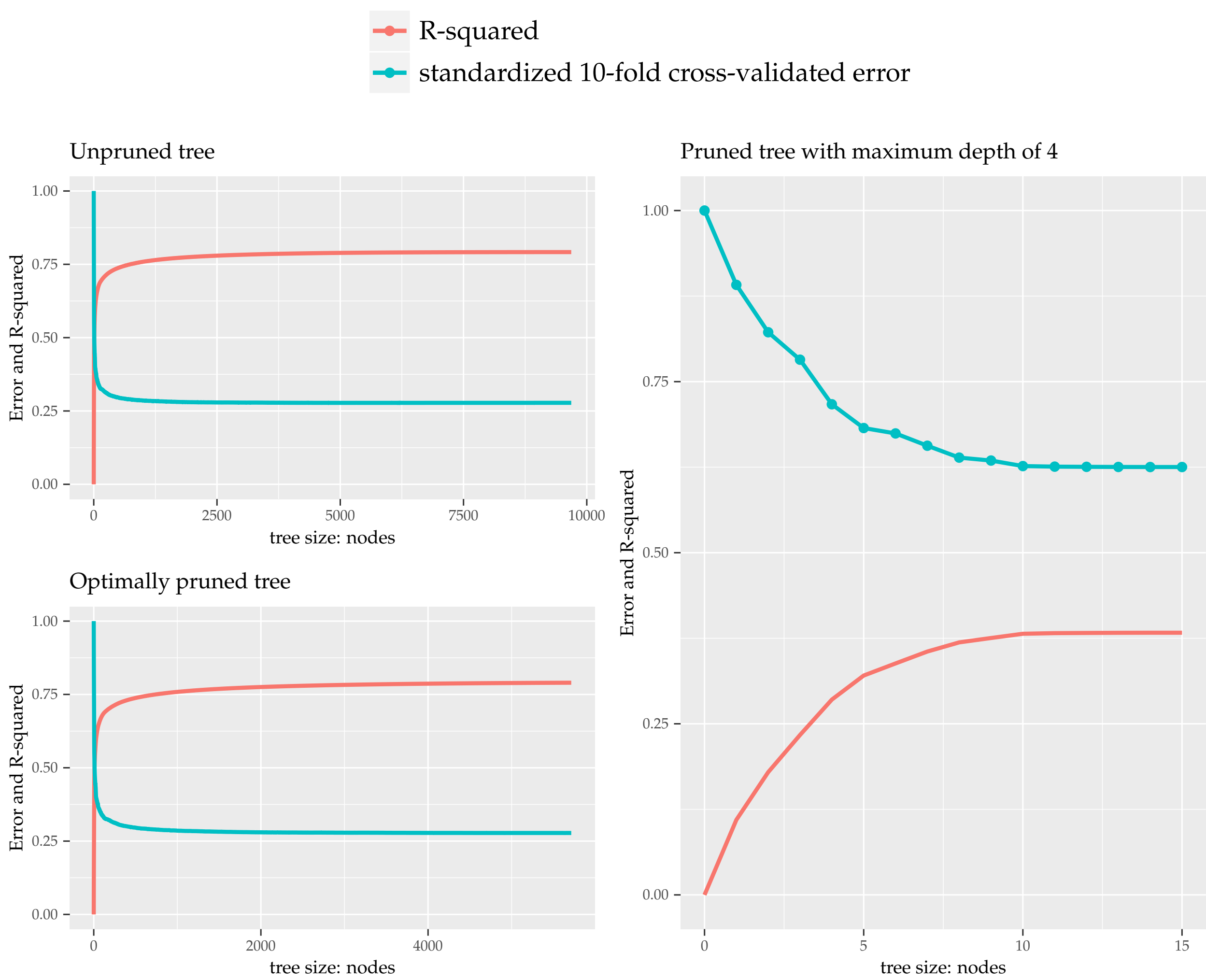


Note: The darker the shade of blue on a box is, the higher the bond specialness premium is in the cluster it summarizes. For visualisation purposes the depth of the trees has been restricted to four. Days subject to seasonal effects (i.e. month-end, quarter-end and year-end) have been removed. We exclude Treasury bills in this example.

C.2 Calibration of regression tree parameters

The parameters for the regression trees presented for the German segment in Annex C.1 are calibrated only with observations following the implementation of the Public Sector Purchases Program in March 2015. The initial unpruned tree is grown until a minimum of 10 observations at a node is reached. Once the unpruned tree is grown, we observe the 10-fold cross-validation normalised error rate and the R^2 as a function of the size of the best tree obtained from applying a loosening cost-complexity pruning parameter (upper left-hand-side of Figure 22 – "Unpruned tree"). The resulting unpruned tree has more than 9,000 nodes. The optimally pruned tree (lower left-hand-side of Figure 22) minimising the error rate still requires around 4,000 nodes. For visualisation, we restricted the depth from root to leaves to just four (see the right-hand-side of Figure 22) – which still yields an R^2 of around 0.3.

Figure 22: Pruning Exercise



C.3 Random Forests

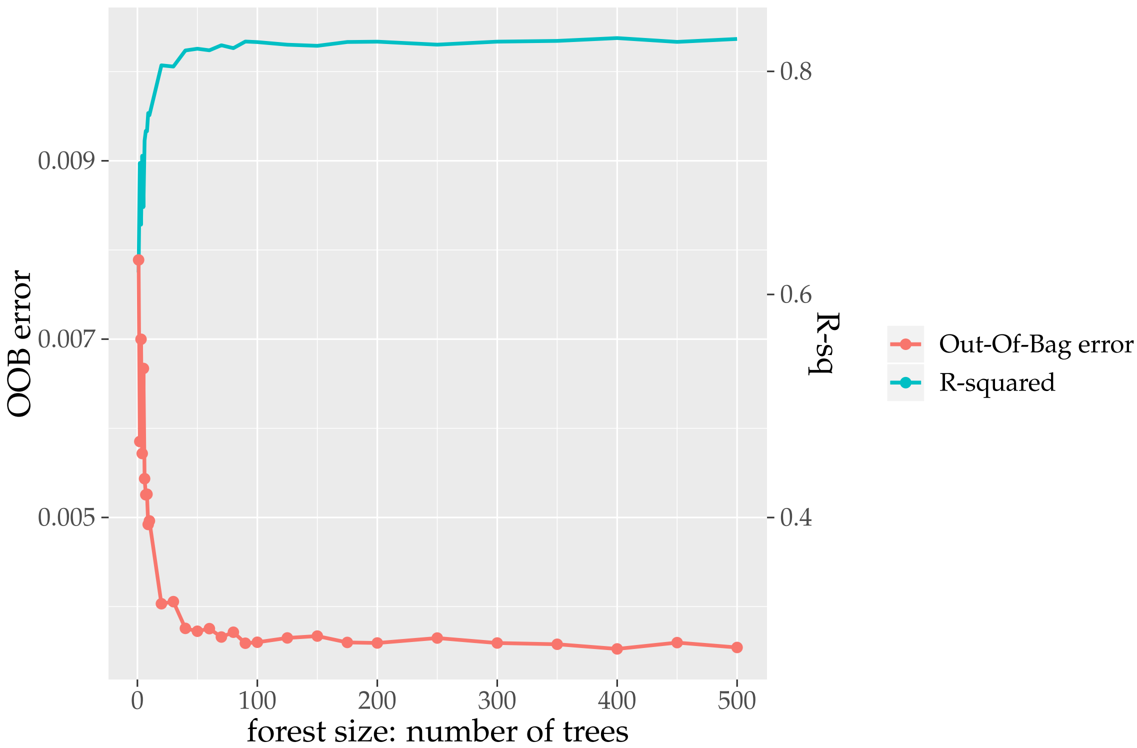
In line with the literature, we grow forests of unpruned trees while only allowing a third of our variables to be considered at each node. After an analysis of the cost of computationally-expensive forest-growing process and the benefits of larger forests in terms of efficiency and consistency of our in-sample predictions, we finally choose to create forests of 200 bagged trees (see the out-of-bags error as a function of the number of trees in Figure 23). We have grown random forests by including a time-trend variable which – through non-linearity – can capture time effects in the data so as to avoid that other time-varying proxies spuriously do so.

Random forests vastly outperform panel regressions in terms of explanatory power, as displayed in Table 6.

Table 6: Explanatory power of models estimating the bond specialness premium

R-squared for:	DE	FR	IT	ES
Random Forests of 500 trees	0.829	0.784	0.771	0.713
Panel data (Pooled)	0.531	0.508	0.262	0.267

Figure 23: Analysis of forest size



D Variable Hierarchy

The following figures show the variable importance measure for the entire set of potential predictors explaining repo premia (See Table 2). The random forests used to construct these Figures are based on 500 trees and the variable importance measure used here is the increase in the mean-squared-error of the model after having permutated observations of a given variable.

Figure 24: Variable Importance: German segment

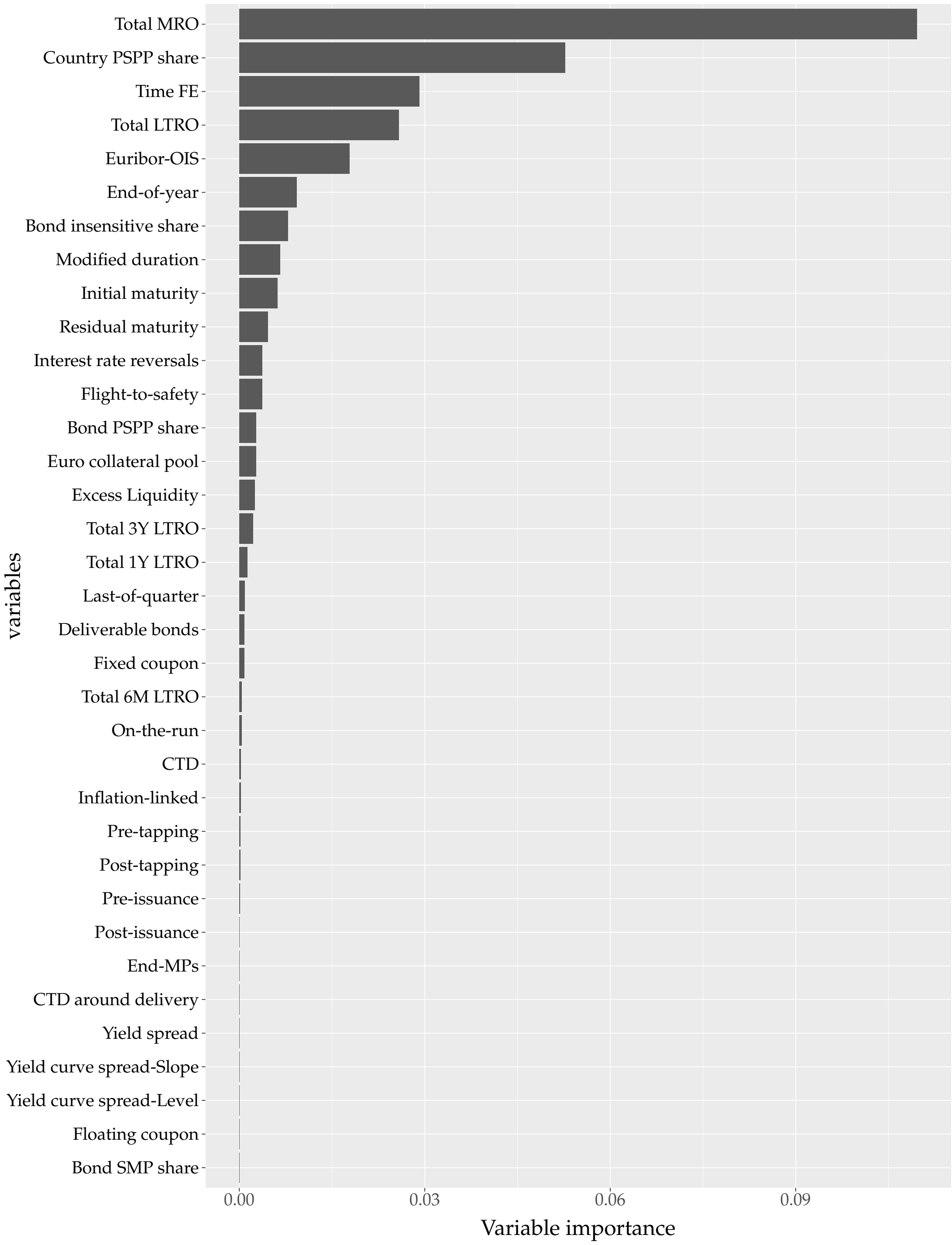


Figure 25: Variable Importance: French segment

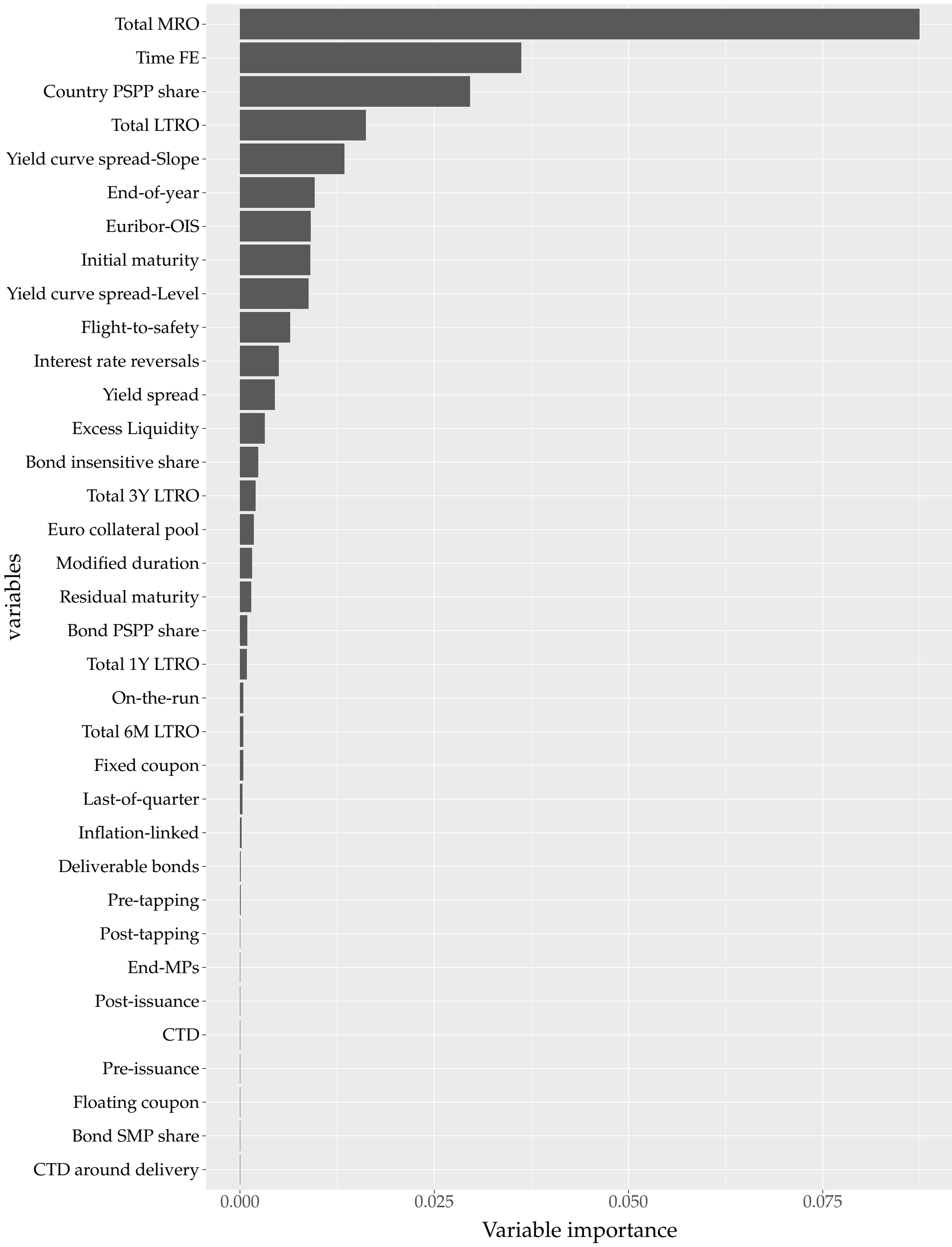


Figure 26: Variable Importance: Italian segment

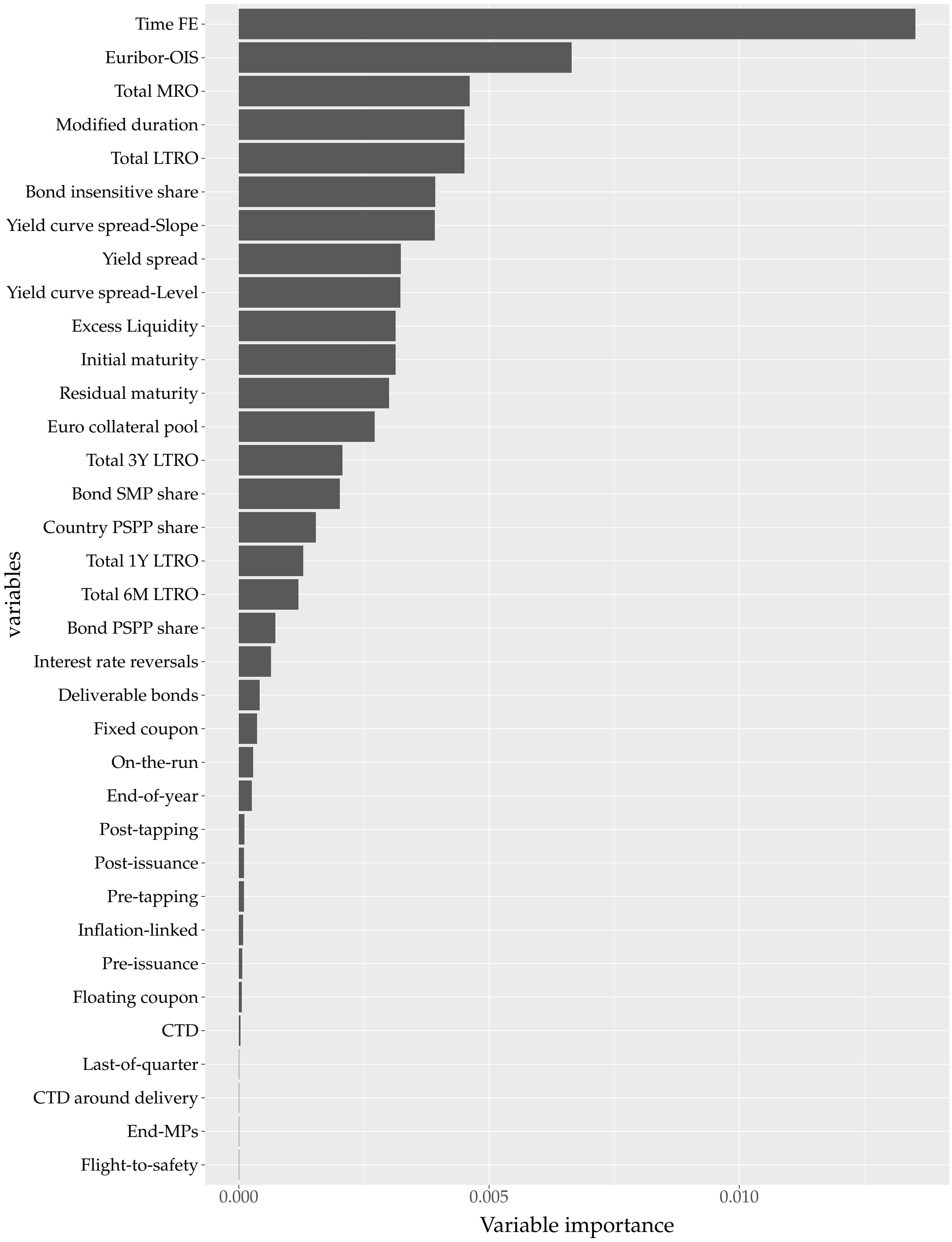
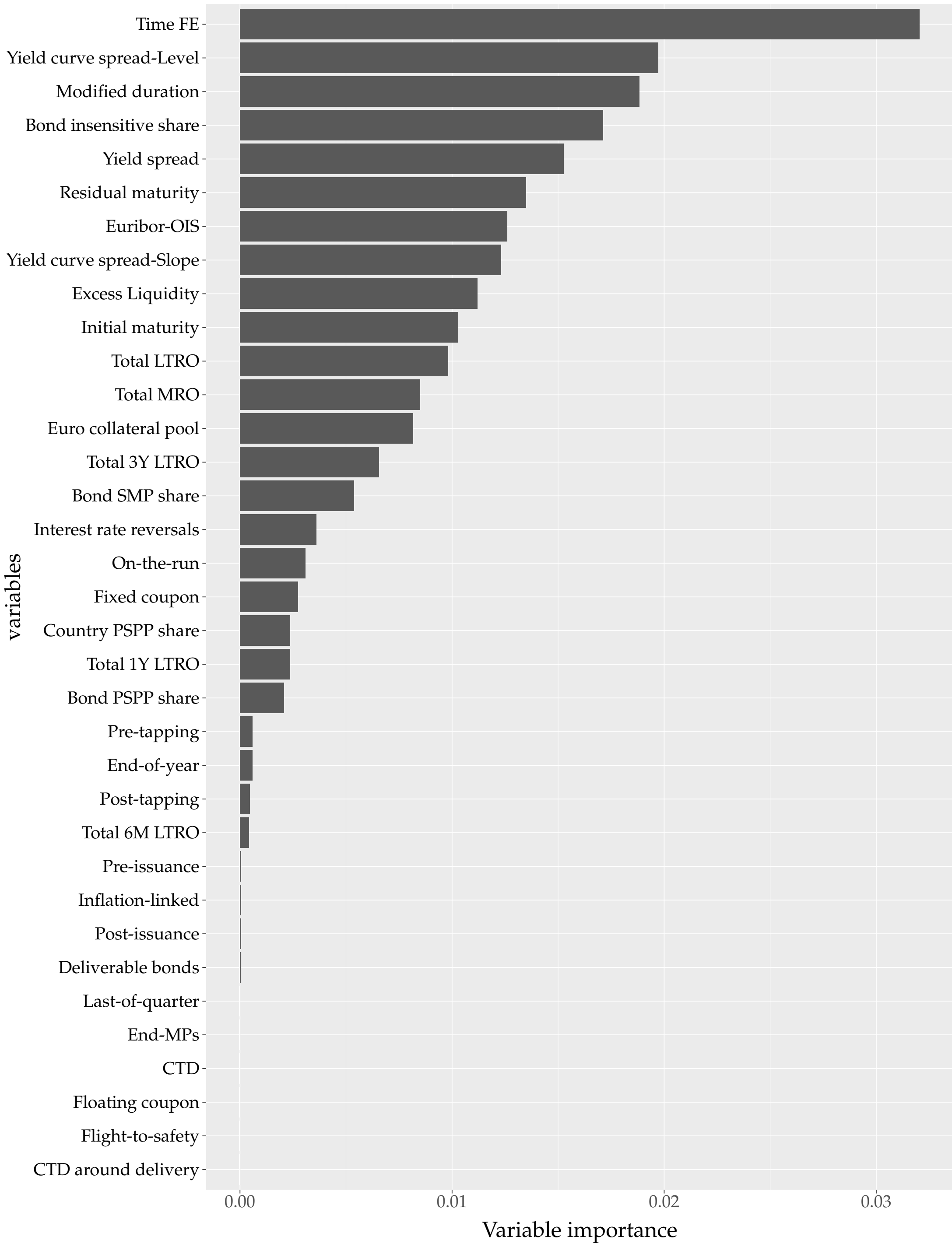


Figure 27: Variable Importance: Spanish segment



E Panel Regression Tables

The following tables show the impact of our main explanatory variables on the bond specialness premium (Annex E.1) and the composite specialness premium (Annex E.2). The tables display confidence intervals at the 99% level for heteroskedastic and consistent errors in bond and time dimensions. They report results from pooled OLS, bond-fixed effects, and time-fixed effects regressions with the inclusion or exclusion of our measure on price insensitive investors ("Bond insensitive share") which starts in January 2014.

E.1 Bond specialness premium

Table 7: Bond specialness: panel regressions

	Pooled - German (1)	Pooled - French (2)	Pooled - Italian (3)	Pooled - Spanish (4)
Total MRO	0.0003*** (0.0002 ; 0.0003)	0.001*** (0.001 ; 0.001)	0.001*** (0.001 ; 0.001)	0.001*** (0.001 ; 0.001)
Dummy for MRO > 160bn	0.002 (−0.001 ; 0.006)	0.026*** (0.022 ; 0.029)	0.020*** (0.017 ; 0.023)	0.008* (−0.002 ; 0.018)
Yield spread		0.048*** (0.044 ; 0.052)	0.023*** (0.022 ; 0.024)	0.055*** (0.052 ; 0.057)
Flight-to-safety	0.001** (0.0001 ; 0.001)	−0.005*** (−0.006 ; −0.004)		
Country PSPP share	0.279*** (0.233 ; 0.325)	0.753*** (0.701 ; 0.804)	0.569*** (0.530 ; 0.607)	−0.095** (−0.189 ; −0.002)
Dummy for Country PSPP share > 20	0.044*** (0.040 ; 0.049)	0.096*** (0.091 ; 0.100)	0.036*** (0.032 ; 0.040)	0.055*** (0.047 ; 0.062)
Bond PSPP share	0.201*** (0.177 ; 0.225)	−0.216*** (−0.250 ; −0.183)	0.123*** (0.105 ; 0.142)	0.248*** (0.207 ; 0.289)
Bond SMP share			0.031*** (0.020 ; 0.043)	0.155*** (0.124 ; 0.186)
Euro collateral pool	0.047*** (0.012 ; 0.082)	−0.069*** (−0.084 ; −0.054)	−0.106*** (−0.116 ; −0.095)	−0.022* (−0.048 ; 0.003)
Modified duration	−0.001*** (−0.002 ; −0.001)	−0.001*** (−0.002 ; −0.001)	−0.001*** (−0.002 ; −0.001)	−0.009*** (−0.011 ; −0.008)
T-bills X Interest rate reversals	6.457*** (5.959 ; 6.955)	3.652*** (3.260 ; 4.044)	2.831*** (2.467 ; 3.195)	0.605 (−0.380 ; 1.590)
T-bills X Country PSPP share	0.557*** (0.495 ; 0.620)	−0.089*** (−0.148 ; −0.029)	−0.250*** (−0.300 ; −0.200)	0.066 (−0.043 ; 0.175)
T-bills X Flight-to-safety	0.011*** (0.010 ; 0.013)	0.026*** (0.025 ; 0.028)		
T-bills X Total MRO	0.0002*** (0.0001 ; 0.0003)	−0.0003*** (−0.0003 ; −0.0002)	−0.0003*** (−0.0004 ; −0.0003)	0.001*** (0.001 ; 0.001)
Enhanced SecLend X Country PSPP share	−0.170*** (−0.213 ; −0.127)	−0.991*** (−1.037 ; −0.945)	−0.177*** (−0.212 ; −0.142)	0.183*** (0.140 ; 0.226)
Enhanced SecLend X Bond PSPP share	0.085*** (0.049 ; 0.120)	0.382*** (0.346 ; 0.419)	−0.065*** (−0.082 ; −0.047)	−0.130*** (−0.168 ; −0.092)
CTD around delivery X Bond PSPP share	1.245*** (1.007 ; 1.483)	−0.047 (−0.302 ; 0.209)	0.145 (−0.112 ; 0.401)	−0.057 (−1.731 ; 1.617)
On-the-run X Bond PSPP share	0.501*** (0.427 ; 0.574)	0.101*** (0.059 ; 0.143)	−0.273*** (−0.306 ; −0.241)	−0.223*** (−0.268 ; −0.178)
Bond specific controls?	Yes	Yes	Yes	Yes
Window dressing controls?	Yes	Yes	Yes	Yes
Observations	140,630	152,095	190,454	79,611
R^2	0.531	0.508	0.262	0.267
Adjusted R^2	0.531	0.508	0.261	0.266

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

E.2 Composite specialness premium

Table 12: Composite spread: panel regressions

	Pooled - German (1)	Pooled - French (2)
Total MRO	0.001*** (0.001 ; 0.001)	0.001*** (0.001 ; 0.001)
Dummy for MRO > 160bn	0.063*** (0.058 ; 0.068)	0.039*** (0.034 ; 0.043)
Yield spread		0.173*** (0.168 ; 0.177)
Flight-to-safety	0.024*** (0.023 ; 0.024)	0.002*** (0.001 ; 0.003)
Country PSPP share	1.040*** (0.983 ; 1.098)	1.789*** (1.730 ; 1.848)
Dummy for Country PSPP share > 20%	0.078*** (0.072 ; 0.083)	0.101*** (0.096 ; 0.106)
Bond PSPP share	0.207*** (0.178 ; 0.235)	−0.101*** (−0.138 ; −0.063)
Euro collateral pool	0.079*** (0.037 ; 0.120)	−0.084*** (−0.102 ; −0.067)
Modified duration	−0.004*** (−0.005 ; −0.003)	−0.001*** (−0.002 ; −0.001)
T-bills X Interest rate reversals	10.860*** (10.290 ; 11.430)	6.628*** (6.196 ; 7.059)
T-bills X Country PSPP share	0.377*** (0.307 ; 0.448)	−0.248*** (−0.317 ; −0.180)
T-bills X Flight-to-safety	0.019*** (0.017 ; 0.021)	0.039*** (0.038 ; 0.041)
T-bills X Total MRO	−0.001*** (−0.001 ; −0.0005)	−0.001*** (−0.001 ; −0.001)
Enhanced SecLend X Country PSPP share	−0.460*** (−0.507 ; −0.413)	−1.389*** (−1.440 ; −1.337)
Enhanced SecLend X Bond PSPP share	0.059*** (0.019 ; 0.099)	0.333*** (0.293 ; 0.373)
CTD around delivery X Bond PSPP share	1.118*** (0.846 ; 1.390)	−0.079 (−0.380 ; 0.223)
On-the-run X Bond PSPP share	0.411*** (0.332 ; 0.490)	0.150*** (0.105 ; 0.195)
Bond specific controls?	Yes	Yes
Window dressing controls?	Yes	Yes
Observations	144,001	157,799
R^2	0.586	0.608
Adjusted R^2	0.586	0.608

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 8: Bond specialness: panel regressions (Germany)

	Pooled	Pooled	Bond fixed-effects	Bond fixed-effects	Time fixed-effects	Time fixed-effects
	(1)	(2)	(3)	(4)	(5)	(6)
Total MRO	0.0003***	0.0004***	0.0002***	0.001***		
	(0.0002 ; 0.0003)	(0.0004 ; 0.001)	(0.0002 ; 0.0002)	(0.0005 ; 0.001)		
Dummy for MRO > 160bn	0.002	0.030***	−0.001	0.030***		
	(−0.001 ; 0.006)	(0.023 ; 0.037)	(−0.004 ; 0.002)	(0.024 ; 0.036)		
Flight-to-safety	0.001**	0.017***	−0.002***	0.031***	0.022***	−0.0001
	(0.0001 ; 0.001)	(0.012 ; 0.022)	(−0.003 ; −0.002)	(0.026 ; 0.036)	(0.020 ; 0.024)	(−0.009 ; 0.009)
Country PSPP share	0.279***	0.693***	0.263***	0.314***		
	(0.233 ; 0.325)	(0.628 ; 0.757)	(0.216 ; 0.311)	(0.239 ; 0.390)		
Dummy for Country PSPP share > 20	0.044***	0.009***	0.031***	0.012***		
	(0.040 ; 0.049)	(0.004 ; 0.014)	(0.026 ; 0.035)	(0.008 ; 0.017)		
Bond PSPP share	0.201***	0.344***	0.284***	0.401***	0.180***	0.335***
	(0.177 ; 0.225)	(0.319 ; 0.369)	(0.258 ; 0.309)	(0.373 ; 0.428)	(0.158 ; 0.202)	(0.312 ; 0.358)
Euro collateral pool	0.047***	0.289***	−0.074***	0.235***	0.058***	0.258***
	(0.012 ; 0.082)	(0.239 ; 0.339)	(−0.122 ; −0.026)	(0.167 ; 0.304)	(0.025 ; 0.091)	(0.213 ; 0.303)
Bond insensitive share		0.190***		0.170***		0.198***
		(0.182 ; 0.199)		(0.158 ; 0.183)		(0.190 ; 0.206)
Modified duration	−0.001***	0.001**	−0.006***	−0.026***	0.0004	0.002***
	(−0.002 ; −0.001)	(0.0002 ; 0.002)	(−0.008 ; −0.005)	(−0.028 ; −0.023)	(−0.0004 ; 0.001)	(0.001 ; 0.003)
T-bills X Interest rate reversals	6.457***	−7.011***	3.169***	−4.949***	4.051***	−5.081***
	(5.959 ; 6.955)	(−8.118 ; −5.904)	(2.602 ; 3.737)	(−5.992 ; −3.907)	(3.594 ; 4.509)	(−6.169 ; −3.994)
T-bills X Country PSPP share	0.557***	0.407***	1.774***	1.884***	0.549***	0.443***
	(0.495 ; 0.620)	(0.318 ; 0.495)	(1.547 ; 2.000)	(1.636 ; 2.133)	(0.492 ; 0.607)	(0.359 ; 0.527)
T-bills X Flight-to-safety	0.011***	0.132***	−0.004**	0.053***	0.011***	0.135***
	(0.010 ; 0.013)	(0.111 ; 0.153)	(−0.007 ; −0.001)	(0.030 ; 0.075)	(0.009 ; 0.012)	(0.114 ; 0.156)
T-bills X Total MRO	0.0002***	0.00004	0.0003***	−0.00002	0.0002***	0.0001*
	(0.0001 ; 0.0003)	(−0.0001 ; 0.0002)	(0.0003 ; 0.0004)	(−0.0001 ; 0.0001)	(0.0001 ; 0.0003)	(−0.00000 ; 0.0003)
Enhanced SecLend X Country PSPP share	−0.170***	−0.300***	−0.109***	−0.137***		
	(−0.213 ; −0.127)	(−0.343 ; −0.257)	(−0.149 ; −0.069)	(−0.179 ; −0.095)		
Enhanced SecLend X Bond PSPP share	0.085***	0.043**	−0.005	−0.086***	0.089***	0.056***
	(0.049 ; 0.120)	(0.007 ; 0.078)	(−0.037 ; 0.028)	(−0.119 ; −0.053)	(0.057 ; 0.122)	(0.024 ; 0.089)
CTD around delivery X Bond PSPP share	1.245***	1.299***	0.863***	0.938***	1.207***	1.289***
	(1.007 ; 1.483)	(1.034 ; 1.565)	(0.670 ; 1.056)	(0.702 ; 1.175)	(0.989 ; 1.424)	(1.052 ; 1.526)
On-the-run X Bond PSPP share	0.501***	0.435***	0.329***	0.607***	0.458***	0.404***
	(0.427 ; 0.574)	(0.332 ; 0.539)	(0.249 ; 0.408)	(0.500 ; 0.714)	(0.393 ; 0.522)	(0.316 ; 0.493)
Bond specific controls?	Yes	Yes	No	No	Yes	Yes
Window dressing controls?	Yes	Yes	Yes	Yes	No	No
Observations	140,630	73,110	140,630	73,110	140,630	73,110
R^2	0.531	0.684	0.516	0.694	0.240	0.316
Adjusted R^2	0.531	0.683	0.515	0.692	0.229	0.305

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 9: Bond specialness: panel regressions (France)

	Pooled	Pooled	Bond fixed-effects	Bond fixed-effects	Time fixed-effects	Time fixed-effects
	(1)	(2)	(3)	(4)	(5)	(6)
Total MRO	0.001***	0.001***	0.0005***	0.001***		
	(0.001 ; 0.001)	(0.001 ; 0.001)	(0.0004 ; 0.001)	(0.001 ; 0.001)		
Dummy for MRO > 160bn	0.026***	0.044***	0.015***	0.044***		
	(0.022 ; 0.029)	(0.038 ; 0.050)	(0.011 ; 0.018)	(0.039 ; 0.050)		
Yield spread	0.048***	0.108***	0.050***	0.101***	0.001	0.115***
	(0.044 ; 0.052)	(0.099 ; 0.117)	(0.046 ; 0.054)	(0.092 ; 0.110)	(−0.004 ; 0.007)	(0.097 ; 0.133)
Flight-to-safety	−0.005***	0.0002	−0.010***	−0.001	0.018***	0.025***
	(−0.006 ; −0.004)	(−0.004 ; 0.004)	(−0.011 ; −0.009)	(−0.005 ; 0.003)	(0.016 ; 0.020)	(0.019 ; 0.030)
Country PSPP share	0.753***	0.956***	0.828***	0.699***		
	(0.701 ; 0.804)	(0.887 ; 1.024)	(0.767 ; 0.890)	(0.614 ; 0.784)		
Dummy for Country PSPP share > 20	0.096***	0.079***	0.091***	0.082***		
	(0.091 ; 0.100)	(0.074 ; 0.084)	(0.087 ; 0.096)	(0.077 ; 0.086)		
Bond PSPP share	−0.216***	−0.167***	−0.037*	−0.017	−0.250***	−0.115***
	(−0.250 ; −0.183)	(−0.201 ; −0.134)	(−0.080 ; 0.005)	(−0.064 ; 0.029)	(−0.278 ; −0.221)	(−0.145 ; −0.085)
Euro collateral pool	−0.069***	0.041***	0.075***	0.099***	−0.024***	0.034***
	(−0.084 ; −0.054)	(0.022 ; 0.059)	(0.051 ; 0.099)	(0.069 ; 0.128)	(−0.036 ; −0.012)	(0.017 ; 0.050)
Bond insensitive share		0.004		0.058***		0.007**
		(−0.002 ; 0.011)		(0.046 ; 0.071)		(0.001 ; 0.013)
Modified duration	−0.001***	−0.002***	0.002***	−0.002*	−0.001***	−0.002***
	(−0.002 ; −0.001)	(−0.003 ; −0.002)	(0.001 ; 0.003)	(−0.004 ; 0.0001)	(−0.002 ; −0.001)	(−0.003 ; −0.002)
T-bills X Interest rate reversals	3.652***	0.050	0.049	1.088***	1.003***	0.716*
	(3.260 ; 4.044)	(−0.650 ; 0.749)	(−0.412 ; 0.510)	(0.355 ; 1.822)	(0.674 ; 1.332)	(−0.003 ; 1.436)
T-bills X Country PSPP share	−0.089***	−0.171***	0.350***	0.576***	−0.122***	−0.227***
	(−0.148 ; −0.029)	(−0.260 ; −0.083)	(0.165 ; 0.534)	(0.365 ; 0.786)	(−0.172 ; −0.072)	(−0.309 ; −0.145)
T-bills X Flight-to-safety	0.026***	0.075***	0.015***	0.092***	0.019***	0.077***
	(0.025 ; 0.028)	(0.063 ; 0.088)	(0.013 ; 0.018)	(0.076 ; 0.108)	(0.018 ; 0.020)	(0.063 ; 0.090)
T-bills X Total MRO	−0.0003***	−0.0002***	−0.0001*	−0.00000	−0.0001***	−0.0003***
	(−0.0003 ; −0.0002)	(−0.0003 ; −0.0001)	(−0.0001 ; 0.00002)	(−0.0001 ; 0.0001)	(−0.0002 ; −0.00005)	(−0.0004 ; −0.0002)
Enhanced SecLend X Country PSPP share	−0.991***	−0.970***	−0.736***	−0.675***		
	(−1.037 ; −0.945)	(−1.016 ; −0.924)	(−0.787 ; −0.684)	(−0.728 ; −0.623)		
Enhanced SecLend X Bond PSPP share	0.382***	0.353***	0.155***	0.121***	0.352***	0.287***
	(0.346 ; 0.419)	(0.316 ; 0.389)	(0.113 ; 0.196)	(0.079 ; 0.164)	(0.319 ; 0.385)	(0.254 ; 0.321)
CTD around delivery X Bond PSPP share	−0.047	0.089	−0.143	0.038	−0.146	0.078
	(−0.302 ; 0.209)	(−0.135 ; 0.312)	(−0.394 ; 0.108)	(−0.184 ; 0.259)	(−0.352 ; 0.059)	(−0.108 ; 0.265)
On-the-run X Bond PSPP share	0.101***	0.100***	0.081**	0.046	0.062***	0.109***
	(0.059 ; 0.143)	(0.042 ; 0.158)	(0.018 ; 0.145)	(−0.042 ; 0.135)	(0.026 ; 0.099)	(0.056 ; 0.161)
Bond specific controls?	Yes	Yes	No	No	Yes	Yes
Window dressing controls?	Yes	Yes	Yes	Yes	No	No
Observations	152,095	79,730	152,095	79,730	152,095	79,730
R^2	0.508	0.677	0.473	0.676	0.238	0.181
Adjusted R^2	0.508	0.677	0.471	0.674	0.227	0.169

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 10: Bond specialness: panel regressions (Italy)

	Pooled	Pooled	Bond fixed-effects	Bond fixed-effects	Time fixed-effects	Time fixed-effects
	(1)	(2)	(3)	(4)	(5)	(6)
Total MRO	0.001^{***}	0.0003^{***}	0.001^{***}	0.0003^{***}		
	(0.001 ; 0.001)	(0.0002 ; 0.0003)	(0.001 ; 0.001)	(0.0002 ; 0.0003)		
Dummy for MRO > 160bn	0.020^{***}	0.034^{***}	0.017^{***}	0.035^{***}		
	(0.017 ; 0.023)	(0.029 ; 0.038)	(0.014 ; 0.020)	(0.031 ; 0.039)		
Yield spread	0.023^{***}	0.036^{***}	0.023^{***}	0.034^{***}	-0.002^{**}	0.010^{***}
	(0.022 ; 0.024)	(0.034 ; 0.039)	(0.022 ; 0.024)	(0.031 ; 0.037)	(−0.004 ; −0.0002)	(0.005 ; 0.015)
Country PSPP share	0.569^{***}	0.045^{**}	0.743^{***}	−0.022		
	(0.530 ; 0.607)	(0.004 ; 0.087)	(0.694 ; 0.792)	(−0.073 ; 0.028)		
Dummy for Country PSPP share > 20	0.036^{***}	0.030^{***}	0.031^{***}	0.028^{***}		
	(0.032 ; 0.040)	(0.027 ; 0.033)	(0.027 ; 0.035)	(0.025 ; 0.032)		
Bond PSPP share	0.123^{***}	0.255^{***}	0.172^{***}	0.309^{***}	0.147^{***}	0.231^{***}
	(0.105 ; 0.142)	(0.240 ; 0.270)	(0.148 ; 0.196)	(0.289 ; 0.330)	(0.131 ; 0.163)	(0.217 ; 0.245)
Bond SMP share	0.031^{***}	0.127^{***}	0.013	1.154^{***}	0.095^{***}	0.129^{***}
	(0.020 ; 0.043)	(0.117 ; 0.138)	(−0.018 ; 0.044)	(0.841 ; 1.468)	(0.085 ; 0.104)	(0.119 ; 0.138)
Euro collateral pool	-0.106^{***}	0.070^{***}	-0.067^{***}	0.062^{***}	0.020^{***}	0.055^{***}
	(−0.116 ; −0.095)	(0.058 ; 0.081)	(−0.081 ; −0.054)	(0.047 ; 0.076)	(0.011 ; 0.029)	(0.045 ; 0.066)
Bond insensitive share		0.103^{***}		0.096^{***}		0.109^{***}
		(0.097 ; 0.109)		(0.087 ; 0.105)		(0.103 ; 0.114)
Modified duration	-0.001^{***}	-0.002^{***}	0.007^{***}	-0.003^{***}	0.0001	-0.002^{***}
	(−0.002 ; −0.001)	(−0.002 ; −0.002)	(0.006 ; 0.008)	(−0.004 ; −0.001)	(−0.0003 ; 0.001)	(−0.002 ; −0.001)
T-bills X Interest rate reversals	2.831^{***}	-0.851^{***}	1.404^{***}	-1.019^{***}	−0.231	-0.995^{***}
	(2.467 ; 3.195)	(−1.346 ; −0.356)	(0.981 ; 1.827)	(−1.542 ; −0.496)	(−0.574 ; 0.112)	(−1.485 ; −0.506)
T-bills X Country PSPP share	-0.250^{***}	-0.067^{*}	-0.149^{**}	0.154^{**}	-0.076^{***}	-0.064^{*}
	(−0.300 ; −0.200)	(−0.150 ; 0.016)	(−0.280 ; −0.019)	(0.003 ; 0.305)	(−0.120 ; −0.032)	(−0.141 ; 0.013)
T-bills X Total MRO	-0.0003^{***}	0.0003^{***}	-0.0003^{***}	0.0001^{**}	0.00005^{*}	0.0002^{***}
	(−0.0004 ; −0.0003)	(0.0001 ; 0.0004)	(−0.0004 ; −0.0002)	(0.00001 ; 0.0002)	(−0.00000 ; 0.0001)	(0.0001 ; 0.0003)
Enhanced SecLend X Country PSPP share	-0.177^{***}	-0.055^{***}	-0.134^{***}	-0.027^{*}		
	(−0.212 ; −0.142)	(−0.084 ; −0.027)	(−0.173 ; −0.095)	(−0.056 ; 0.002)		
Enhanced SecLend X Bond PSPP share	-0.065^{***}	-0.107^{***}	-0.088^{***}	-0.118^{***}	-0.046^{***}	-0.072^{***}
	(−0.082 ; −0.047)	(−0.122 ; −0.093)	(−0.108 ; −0.069)	(−0.134 ; −0.103)	(−0.062 ; −0.031)	(−0.087 ; −0.058)
CTD around delivery X Bond PSPP share	0.145	0.094	0.129	0.051	0.104	0.072
	(−0.112 ; 0.401)	(−0.099 ; 0.287)	(−0.110 ; 0.367)	(−0.129 ; 0.231)	(−0.114 ; 0.321)	(−0.108 ; 0.251)
On-the-run X Bond PSPP share	-0.273^{***}	-0.242^{***}	-0.056^{***}	-0.134^{***}	-0.252^{***}	-0.223^{***}
	(−0.306 ; −0.241)	(−0.275 ; −0.209)	(−0.089 ; −0.022)	(−0.170 ; −0.098)	(−0.281 ; −0.222)	(−0.255 ; −0.191)
Bond specific controls?	Yes	Yes	No	No	Yes	Yes
Window dressing controls?	Yes	Yes	Yes	Yes	No	No
Observations	190,454	102,898	190,454	102,898	190,454	102,898
R^2	0.262	0.277	0.219	0.212	0.084	0.212
Adjusted R^2	0.261	0.275	0.217	0.209	0.074	0.203

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 11: Bond specialness: panel regressions (Spain)

	Pooled	Pooled	Bond fixed-effects	Bond fixed-effects	Time fixed-effects	Time fixed-effects
	(1)	(2)	(3)	(4)	(5)	(6)
Total MRO	0.001***	0.001***	0.001***	0.001***		
	(0.001 ; 0.001)	(0.001 ; 0.001)	(0.001 ; 0.001)	(0.001 ; 0.001)		
Dummy for MRO > 160bn	0.008*	0.031***	0.007	0.032***		
	(−0.002 ; 0.018)	(0.021 ; 0.041)	(−0.003 ; 0.017)	(0.022 ; 0.042)		
Yield spread	0.055***	0.069***	0.048***	0.061***	0.022***	0.016***
	(0.052 ; 0.057)	(0.063 ; 0.076)	(0.045 ; 0.051)	(0.055 ; 0.068)	(0.015 ; 0.030)	(0.005 ; 0.027)
Country PSPP share	−0.095**	−0.076*	0.189***	0.451***		
	(−0.189 ; −0.002)	(−0.159 ; 0.007)	(0.075 ; 0.304)	(0.353 ; 0.550)		
Dummy for Country PSPP share > 20	0.055***	0.049***	0.038***	0.028***		
	(0.047 ; 0.062)	(0.045 ; 0.054)	(0.031 ; 0.045)	(0.023 ; 0.032)		
Bond PSPP share	0.248***	0.277***	0.235***	0.332***	0.216***	0.262***
	(0.207 ; 0.289)	(0.250 ; 0.305)	(0.177 ; 0.293)	(0.291 ; 0.374)	(0.178 ; 0.254)	(0.237 ; 0.287)
Bond SMP share	0.155***	0.144***	0.308***	0.580***	0.144***	0.137***
	(0.124 ; 0.186)	(0.120 ; 0.168)	(0.206 ; 0.409)	(0.206 ; 0.955)	(0.115 ; 0.173)	(0.115 ; 0.158)
Euro collateral pool	−0.022*	0.005	0.036**	0.100***	−0.003	−0.019*
	(−0.048 ; 0.003)	(−0.020 ; 0.029)	(0.005 ; 0.066)	(0.072 ; 0.129)	(−0.028 ; 0.023)	(−0.040 ; 0.003)
Bond insensitive share		0.092***		0.180***		0.124***
		(0.079 ; 0.105)		(0.161 ; 0.199)		(0.112 ; 0.136)
Modified duration	−0.009***	−0.001	−0.003***	0.002***	−0.008***	0.001
	(−0.011 ; −0.008)	(−0.002 ; 0.001)	(−0.005 ; −0.002)	(0.0004 ; 0.003)	(−0.009 ; −0.006)	(−0.0005 ; 0.002)
T-bills X Interest rate reversals	0.605	1.272***	1.341**	2.035***	−1.760***	0.799*
	(−0.380 ; 1.590)	(0.323 ; 2.221)	(0.264 ; 2.418)	(1.091 ; 2.980)	(−2.781 ; −0.739)	(−0.139 ; 1.736)
T-bills X Country PSPP share	0.066	−0.099*	0.804***	0.022	0.201***	0.055
	(−0.043 ; 0.175)	(−0.222 ; 0.024)	(0.620 ; 0.988)	(−0.165 ; 0.209)	(0.096 ; 0.306)	(−0.058 ; 0.168)
T-bills X Total MRO	0.001***	0.0005***	0.001***	0.0002**	0.001***	0.001***
	(0.001 ; 0.001)	(0.0003 ; 0.001)	(0.0004 ; 0.001)	(0.00000 ; 0.0004)	(0.001 ; 0.001)	(0.0004 ; 0.001)
Enhanced SecLend X Country PSPP share	0.183***	0.196***	−0.043*	−0.002		
	(0.140 ; 0.226)	(0.162 ; 0.230)	(−0.096 ; 0.010)	(−0.040 ; 0.035)		
Enhanced SecLend X Bond PSPP share	−0.130***	−0.161***	−0.021	−0.086***	−0.107***	−0.142***
	(−0.168 ; −0.092)	(−0.188 ; −0.135)	(−0.065 ; 0.023)	(−0.115 ; −0.057)	(−0.143 ; −0.072)	(−0.166 ; −0.117)
CTD around delivery X Bond PSPP share	−0.057	−0.183	−0.333	0.170	−0.042	−0.235
	(−1.731 ; 1.617)	(−0.979 ; 0.613)	(−1.994 ; 1.327)	(−0.570 ; 0.910)	(−1.572 ; 1.487)	(−0.916 ; 0.446)
On-the-run X Bond PSPP share	−0.223***	−0.041**	−0.229***	−0.234***	−0.218***	−0.062***
	(−0.268 ; −0.178)	(−0.079 ; −0.004)	(−0.282 ; −0.176)	(−0.280 ; −0.188)	(−0.261 ; −0.175)	(−0.097 ; −0.027)
Bond specific controls?	Yes	Yes	No	No	Yes	Yes
Window dressing controls?	Yes	Yes	Yes	Yes	No	No
Observations	79,611	50,802	79,611	50,802	79,611	50,802
R^2	0.267	0.271	0.180	0.172	0.123	0.250
Adjusted R^2	0.266	0.270	0.177	0.169	0.100	0.233

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 13: Composite spread: panel regressions (Germany)

	Pooled	Pooled	Bond fixed-effects	Bond fixed-effects	Time fixed-effects	Time fixed-effects
	(1)	(2)	(3)	(4)	(5)	(6)
Total MRO	0.001***	0.001***	0.001***	0.001***		
	(0.001 ; 0.001)	(0.001 ; 0.001)	(0.001 ; 0.001)	(0.001 ; 0.001)		
Dummy for MRO > 160bn	0.063***	−0.027***	0.054***	−0.026***		
	(0.058 ; 0.068)	(−0.035 ; −0.019)	(0.049 ; 0.059)	(−0.034 ; −0.019)		
Flight-to-safety	0.024***	0.059***	0.017***	0.074***	0.022***	−0.002
	(0.023 ; 0.024)	(0.054 ; 0.064)	(0.016 ; 0.018)	(0.069 ; 0.079)	(0.020 ; 0.024)	(−0.011 ; 0.008)
Country PSPP share	1.040***	1.444***	1.223***	1.079***		
	(0.983 ; 1.098)	(1.372 ; 1.516)	(1.162 ; 1.285)	(0.995 ; 1.163)		
Dummy for Country PSPP share > 20%	0.078***	0.036***	0.057***	0.037***		
	(0.072 ; 0.083)	(0.031 ; 0.041)	(0.052 ; 0.063)	(0.032 ; 0.042)		
Bond PSPP share	0.207***	0.378***	0.315***	0.411***	0.180***	0.334***
	(0.178 ; 0.235)	(0.351 ; 0.405)	(0.283 ; 0.347)	(0.381 ; 0.442)	(0.158 ; 0.201)	(0.310 ; 0.357)
Euro collateral pool	0.079***	0.262***	0.070**	0.192***	0.058***	0.246***
	(0.037 ; 0.120)	(0.207 ; 0.316)	(0.008 ; 0.131)	(0.117 ; 0.267)	(0.026 ; 0.091)	(0.202 ; 0.290)
Bond insensitive share		0.193***		0.176***		0.199***
		(0.184 ; 0.202)		(0.163 ; 0.190)		(0.191 ; 0.207)
Modified duration	−0.004***	0.001	−0.007***	−0.028***	0.0002	0.002***
	(−0.005 ; −0.003)	(−0.0003 ; 0.002)	(−0.009 ; −0.005)	(−0.031 ; −0.025)	(−0.001 ; 0.001)	(0.001 ; 0.003)
T-bills X Interest rate reversals	10.860***	−8.889***	7.000***	−6.354***	4.427***	−4.975***
	(10.290 ; 11.430)	(−10.090 ; −7.690)	(6.337 ; 7.662)	(−7.485 ; −5.223)	(3.945 ; 4.910)	(−6.093 ; −3.856)
T-bills X Country PSPP share	0.377***	0.335***	1.366***	1.859***	0.584***	0.512***
	(0.307 ; 0.448)	(0.237 ; 0.432)	(1.120 ; 1.612)	(1.591 ; 2.126)	(0.526 ; 0.641)	(0.426 ; 0.597)
T-bills X Flight-to-safety	0.019***	0.155***	0.013***	0.071***	0.014***	0.132***
	(0.017 ; 0.021)	(0.132 ; 0.179)	(0.009 ; 0.017)	(0.046 ; 0.095)	(0.012 ; 0.016)	(0.110 ; 0.155)
T-bills X Total MRO	−0.001***	−0.0001	−0.0004***	−0.0002***	0.0002***	0.0003***
	(−0.001 ; −0.0005)	(−0.0002 ; 0.0001)	(−0.0005 ; −0.0003)	(−0.0004 ; −0.0001)	(0.0002 ; 0.0003)	(0.0001 ; 0.0004)
Enhanced SecLend X Country PSPP share	−0.460***	−0.550***	−0.436***	−0.394***		
	(−0.507 ; −0.413)	(−0.596 ; −0.504)	(−0.482 ; −0.391)	(−0.439 ; −0.349)		
Enhanced SecLend X Bond PSPP share	0.059***	−0.002	−0.042**	−0.132***	0.087***	0.054***
	(0.019 ; 0.099)	(−0.040 ; 0.036)	(−0.079 ; −0.004)	(−0.168 ; −0.096)	(0.054 ; 0.120)	(0.020 ; 0.087)
CTD around delivery X Bond PSPP share	1.118***	1.239***	0.751***	0.887***	1.141***	1.222***
	(0.846 ; 1.390)	(0.964 ; 1.514)	(0.519 ; 0.984)	(0.641 ; 1.132)	(0.918 ; 1.363)	(0.986 ; 1.457)
On-the-run X Bond PSPP share	0.411***	0.456***	0.295***	0.659***	0.477***	0.438***
	(0.332 ; 0.490)	(0.351 ; 0.562)	(0.207 ; 0.382)	(0.549 ; 0.769)	(0.414 ; 0.541)	(0.350 ; 0.525)
Bond specific controls?	Yes	Yes	No	No	Yes	Yes
Window dressing controls?	Yes	Yes	Yes	Yes	No	No
Observations	144,001	75,787	144,001	75,787	144,001	75,787
R^2	0.586	0.767	0.561	0.770	0.248	0.316
Adjusted R^2	0.586	0.766	0.560	0.769	0.237	0.306

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Table 14: Composite spread: panel regressions (France)

	Pooled (1)	Pooled (2)	Bond fixed-effects (3)	Bond fixed-effects (4)	Time fixed-effects (5)	Time fixed-effects (6)
Total MRO	0.001***	0.001***	0.001***	0.001***		
	(0.001 ; 0.001)	(0.001 ; 0.001)	(0.001 ; 0.001)	(0.001 ; 0.001)		
Dummy for MRO > 160bn	0.039***	0.007**	0.024***	0.009***		
	(0.034 ; 0.043)	(0.001 ; 0.014)	(0.020 ; 0.028)	(0.003 ; 0.015)		
Yield spread	0.173***	0.091***	0.175***	0.084***	0.0001	0.105***
	(0.168 ; 0.177)	(0.081 ; 0.100)	(0.170 ; 0.179)	(0.074 ; 0.094)	(−0.005 ; 0.006)	(0.087 ; 0.123)
Flight-to-safety	0.002***	0.020***	−0.004***	0.018***	0.019***	0.025***
	(0.001 ; 0.003)	(0.016 ; 0.024)	(−0.005 ; −0.003)	(0.014 ; 0.023)	(0.017 ; 0.020)	(0.019 ; 0.030)
Country PSPP share	1.789***	1.844***	2.019***	1.634***		
	(1.730 ; 1.848)	(1.771 ; 1.917)	(1.947 ; 2.091)	(1.542 ; 1.726)		
Dummy for Country PSPP share > 20%	0.101***	0.102***	0.091***	0.103***		
	(0.096 ; 0.106)	(0.096 ; 0.107)	(0.086 ; 0.096)	(0.098 ; 0.108)		
Bond PSPP share	−0.101***	−0.085***	0.077***	0.067***	−0.217***	−0.067***
	(−0.138 ; −0.063)	(−0.121 ; −0.049)	(0.028 ; 0.125)	(0.016 ; 0.118)	(−0.246 ; −0.188)	(−0.097 ; −0.037)
Euro collateral pool	−0.084***	0.023**	0.076***	0.074***	−0.031***	0.029***
	(−0.102 ; −0.067)	(0.004 ; 0.043)	(0.048 ; 0.104)	(0.041 ; 0.106)	(−0.043 ; −0.020)	(0.013 ; 0.046)
Bond insensitive share		0.008**		0.064***		0.009***
		(0.001 ; 0.014)		(0.052 ; 0.077)		(0.003 ; 0.015)
Modified duration	−0.001***	−0.002***	0.005***	−0.001	−0.001***	−0.002***
	(−0.002 ; −0.001)	(−0.003 ; −0.002)	(0.003 ; 0.006)	(−0.003 ; 0.001)	(−0.002 ; −0.001)	(−0.003 ; −0.002)
T-bills X Interest rate reversals	6.628***	−1.696***	2.858***	0.013	2.105***	0.629*
	(6.196 ; 7.059)	(−2.422 ; −0.969)	(2.326 ; 3.389)	(−0.749 ; 0.775)	(1.773 ; 2.437)	(−0.086 ; 1.345)
T-bills X Country PSPP share	−0.248***	−0.352***	−0.068	0.193*	−0.076***	−0.187***
	(−0.317 ; −0.180)	(−0.447 ; −0.257)	(−0.268 ; 0.132)	(−0.032 ; 0.417)	(−0.126 ; −0.026)	(−0.268 ; −0.106)
T-bills X Flight-to-safety	0.039***	0.081***	0.036***	0.094***	0.016***	0.071***
	(0.038 ; 0.041)	(0.067 ; 0.095)	(0.032 ; 0.039)	(0.077 ; 0.111)	(0.014 ; 0.017)	(0.058 ; 0.085)
T-bills X Total MRO	−0.001***	−0.0004***	−0.001***	−0.0003***	0.0001***	−0.0002***
	(−0.001 ; −0.001)	(−0.001 ; −0.0003)	(−0.001 ; −0.0005)	(−0.0005 ; −0.0002)	(0.00002 ; 0.0001)	(−0.0003 ; −0.0001)
Enhanced SecLend X Country PSPP share	−1.389***	−1.330***	−1.204***	−1.064***		
	(−1.440 ; −1.337)	(−1.379 ; −1.281)	(−1.262 ; −1.145)	(−1.121 ; −1.007)		
Enhanced SecLend X Bond PSPP share	0.333***	0.262***	0.139***	0.053**	0.302***	0.248***
	(0.293 ; 0.373)	(0.223 ; 0.301)	(0.092 ; 0.185)	(0.007 ; 0.100)	(0.269 ; 0.335)	(0.214 ; 0.282)
CTD around delivery X Bond PSPP share	−0.079	0.042	−0.196	−0.017	−0.209**	0.044
	(−0.380 ; 0.223)	(−0.201 ; 0.284)	(−0.489 ; 0.097)	(−0.257 ; 0.224)	(−0.408 ; −0.011)	(−0.133 ; 0.222)
On-the-run X Bond PSPP share	0.150***	0.139***	0.159***	0.115***	0.076***	0.130***
	(0.105 ; 0.195)	(0.081 ; 0.198)	(0.094 ; 0.224)	(0.030 ; 0.201)	(0.040 ; 0.112)	(0.080 ; 0.179)
Bond specific controls?	Yes	Yes	No	No	Yes	Yes
Window dressing controls?	Yes	Yes	Yes	Yes	No	No
Observations	157,799	81,906	157,799	81,906	157,799	81,906
R^2	0.608	0.757	0.575	0.751	0.269	0.185
Adjusted R^2	0.608	0.757	0.573	0.750	0.259	0.173

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Acknowledgements

We are grateful for suggestions by and discussions with Katrin Assenmacher, Lennart Brandt, Pierre Collin-Dufresne, Richard Comotto (ICMA), Jens Eisenschmidt,Wolfgang Lemke, Angela Maddaloni, Fulvio Pegoraro, Robin Tietz, Thomas Werner and Jan Wrampelmeyer. We would like to thank Alexia Ventula Veghazy for her support with the Securities Holdings Statistics. The views expressed here are solely the responsibility of authors and should not be interpreted as reflecting the views of the European Central Bank.

Claus Brand
European Central Bank, Frankfurt am Main, Germany; email: claus.brand@ecb.europa.eu

Lorenzo Ferrante
European Central Bank, Frankfurt am Main, Germany; email: lorenzo.ferrante@ecb.europa.eu

Antoine Hubert
European Central Bank, Frankfurt am Main, Germany; email: antoine.hubert@ecb.europa.eu

Postal address 60640 Frankfurt am Main, Germany
Telephone +49 69 1344 0
Website www.ecb.europa.eu

PDF ISBN 978-92-899-3494-7 ISSN 1725-2806 doi:10.2866/58693 QB-AR-19-013-EN-N