Is the bond market competitive? Evidence from the ECB's asset purchase programme*

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Abstract

We document a recurring pattern in German sovereign bond prices during the Eurosystem's Public Sector Purchase Program (PSPP): a predictable rise towards month-end, followed by a subsequent drop. We propose a sequential search-bargaining model, capturing salient elements of the PSPP's implementation, such as the commitment to transact within an explicit time horizon. The model suggests that this predictable pattern emerges as a consequence of imperfect competition among dealers who are counterparties to the Eurosystem. Predicated on the model's implications, we find that the price fluctuations are markedly accentuated: (a) for bonds specifically targeted by the PSPP, (b) during monthly intervals wherein the Eurosystem engages with a lower number of counterparties, and (c) when the Eurosystem aims for a larger purchase amount. Finally, we explore the potential consequences of our findings for the design and implementation of future asset purchase programs.

Keywords: Quantitative Easing, Sequential Search-Bargaining Model, Imperfect Competition, Dealers, Financial Market Design

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1 Introduction

In the aftermath of the great financial crisis, numerous central banks around the world have engaged in large scale asset purchases. These asset purchases primarily served as a tool for unconventional monetary policy and, as a result, much research has focused on assessing whether and how these programs accomplished their macroeconomic objectives of stimulating inflation and economic growth.[1] However, these purchases also constitute a unique opportunity to explore the market microstructure of sovereign bond markets. These markets typically operate over-the-counter (OTC) with a select group of dealers playing a central role in intermediating trades. It is often argued that having specific dealers with exclusive rights to trade government securities ensures market liquidity and fosters efficient and deep secondary markets. It is thus interesting to investigate whether central banks engaging in these large purchases indeed buy securities at efficient prices. This investigation is beneficial for two primary reasons. First, it can contribute to better design the implementation of (future) purchase programs. Secondly, it offers insights into the OTC structure organized around a limited number of liquidity providers, and more specifically, whether this market structure achieves prices that approach competitive levels.

In this paper, we focus on the Public Sector Purchase Program (PSPP), announced on January 22, 2015, by the European Central Bank (ECB).[2] Despite the program's primary focus on the most liquid euro area sovereign bonds, we document systematic pricing patterns. Specifically, the prices (yields) of German government bonds eligible for the PSPP consistently increased (decreased) leading up to each month-end, decreasing (increasing) thereafter, during the PSPP's implementation from 2015 to 2017. Figure 6 illustrates this pronounced $\cap$-shaped pattern in the holding returns of these bonds. This pattern holds true when we exclude the end-of-quarter windows, account for repo funding costs, omit newly issued bonds, and exclude bonds entering the German sovereign benchmark indexes. Notably, we do not observe a comparable pattern for German government bonds ineligible for the PSPP. A salient feature of the PSPP is that purchased securities must fulfill a set of eligibility criteria compared to other large investors. In our sample period, the key eligibility parameter was that the yield of bonds had to be above the ECB deposit facility rate.

[1]See, for example, Koijen et al. (2021), Di Maggio, Kermani, and Palmer (2020), Gagnon et al. (2011).

[2]The initial program encompassed purchases of 60 billion euros per month from March 2015 to March 2016. Subsequently, the program expanded to 80 billion euros per month until March 2017, followed by a reduction to 60 billion euros per month until December 2017.

We document that on average only 50% of the German central sovereign securities were eligible for PSPP purchases during our sample period.[3]

What could explain such a surprising price pattern? We develop a simple theoretical search-bargaining model that incorporates salient features of the PSPP such as the commitment to buy within an explicit time horizon and shows. Our model shows that the observed pattern can be a result of imperfect competition among dealers providing liquidity. In our model, a single buyer (the central bank) contacts the same N dealers across multiple trading rounds to purchase a finite number of securities.[4]

We assume that the central bank has a reservation price that is known to all dealers and that exceeds the cost to the dealers of providing the asset. The central bank contacts all dealers in every round, but each dealer provides a quote only with some probability, assumed to be strictly less than one to reflect the possible lack of available inventory of the targeted security (or the inability to locate the desired security at sufficient speed).[5] Dealers who provide a quote do so to maximize their expected profit from selling to the central bank over the T trading rounds. The central bank purchases securities so as to minimize its total expected cost for acquiring the targeted number of securities by T. We derive the equilibrium distribution of quoted prices by dealers, as well as the equilibrium average transaction prices at which the central bank will acquire targeted securities in every round.

The model generates increasing average transaction prices and price-dispersion as time approaches maturity. The intuition is that in every round contacted dealers are competing with other dealers contacted in that same round as well as with dealers that will be contacted in subsequent rounds. Therefore competition is highest the more rounds of trading are expected and the fewer securities the central bank wants to purchase. As maturity approaches, contacted dealers realize that they have increasing bargaining power and, in equilibrium, quote from a density whose mean

[3] At the end of our sample, on January 19, 2017, the ECB governing council decided to relax this rule, allowing for further purchases of bonds with a yield below the deposit facility rate as necessary. This made numerous German government bonds potentially eligible again. See discussions in Sections 2 and 3.

[4] Our model builds on the insights from the consumer search literature, such as Weitzman (1979), Stahl (1989), Janssen, Moraga-Gonzalez, and Wildenbeest (2005), which have been applied to OTC markets by Duffie, Dworczak, and Zhu (2017) and Vogel (2020) among others. The aforementioned papers typically consider a single period search-matching game between a continuum of buyers and a finite number of sellers.

[5] Alternatively, this probability reflects the current purchase protocol in place, whereby the central bank only contacts a few (3-4) dealers from the full set at every trading rounds. We discuss the current trading protocol in Section 2.1.

is closer to the reservation price of the central bank. For intuition, consider the case where at most one dealer can quote a price in every round, then clearly in the last round any dealer, realizing that she is the only one quoting, would quote the maximum reservation price, thus extracting all the surplus. In earlier rounds, dealers experience more competition and thus quote from an equilibrium density that is closer to their cost. The central bank buys in every round at the lowest price quoted by any of the dealers, if that minimum price is lower than the expected minimum price that will be offered in subsequent rounds. In equilibrium, we observe that the average transaction price increases over the trading rounds as we approach maturity.

The model makes a number of other qualitative predictions that we can investigate in the data. First, we expect that the price pattern should be more pronounced the more market power the dealers have, that is the larger the targeted asset purchases, the fewer the number of quoting dealers, and the more impatient the central bank is to fill its quota. Second, the model predicts that the cross-sectional variation in transaction prices and quotes should be larger as we approach the target date (the end-of-month in our data).

To test these predictions, we use data on the Eurosystem's PSSP from 2015 to 2017, focusing on German government bonds for several reasons. Firstly, German government debt is considered the "safe asset" in the euro area and is the most liquid (Corradin and Schwaab (2023)). Secondly, a unique feature of the PSPP is that the allocation of purchases across countries is based on the ECB's capital key, with each National Central Bank buying bonds only from its own country, while the ECB purchases bonds from all countries (Hammermann et al. (2019), Bundesbank (2018)).[6] The ECB's capital key is an equal-weighted average of GDP and population shares, revised infrequently. Since Germany has the highest ECB capital key, approximately 27%, the PSPP purchases are significantly skewed towards this country, thus providing an implicit monthly target.[7] As a result, the Eurosystem became the largest holder of German sovereign bonds in the euro area holding more than 24% of the outstanding amount at the end of 2017 (Bundesbank (2018)).

First, we document that price pressure is stronger for the targeted bonds that are actually bought on a day relative to bonds not purchased by the Eurosystem. Crucially, for eligible bonds, the lowest point is reached at the end of the month, while for purchased bonds, the lowest point is

[6]More details on the PSPP implementation are provided in Section 2.1.

[7]The other two major countries are France and Italy, with a capital key of 20.7% and 18% respectively.

reached two days before the end of the month. This aligns with the last day in a given month where Eurosystem trades count towards the monthly purchase targets, as it takes two trading days to settle the trade. This suggests that price pattern is directly linked to the Eurosystem's purchasing activity. When we study the determinants of the daily purchase decision for German sovereign bonds, we find the decision is mainly affected by the eligibility criteria unique to the Eurosystem.

Second, we find that during periods where the Eurosystem targets larger purchase amounts, the price pressure is significantly more pronounced. To avoid the lower liquidity during summer months, the Eurosystem decided to front-load its purchases, acquiring larger amounts during May, June, and November than during July, August, and December. This is particularly interesting since 'front-loading' of purchases was implemented to avoid trading during summer and end-of-year months, which are typically less liquid. It suggests that the pattern is not directly linked to bond market liquidity. Instead, this finding is consistent with our model that a higher purchase target implies greater bargaining power for the dealers.

Third, we find that price pressure is significantly more pronounced in months where the Eurosystem trades with fewer counterparties. This observation is consistent with the model implication that when fewer counterparties quote a price, their individual bargaining power increases, leading to a larger surplus they can extract.

Fourth, we find that the price pressure is much more pronounced around the end of quarters. It is well-known that dealer banks are more balance-sheet constrained around the end of quarters (Arrata et al. (2020), Corradin et al. (2020), Breckenfelder and Ivashina (2021), and Munyan (2017)). This could imply a decreased level of competition among dealers around end-of-quarters. Further studies will be needed to confirm these results. Overall, our evidence seems consistent with our simple model of imperfect competition, where the central bank is bargaining with a limited set of dealers over a finite number of rounds.

Last, we compute an expected shortfall to provide an estimate of the impact of bond prices increasing at the end of the month on the Eurosystem. The expected shortfall is a standard metric in the market microstructure literature (Perold (1988)) used to measure the extent of market illiquidity and does not imply a market loss for the Eurosystem.[8] Specifically, we compute the difference between the value of the total purchases in the last 10 days of each month and the value

[8]See the discussion in Section 5.3.

of the purchases executed at the mid-of-month prices. Based on our estimates, the impact due to the difference in prices of German sovereign bonds is on average euro 14.7 million per month of the market value of the securities purchased in the last 10 days of each month. The total yearly impact amounts to euro 169 million during our sample period. In addition, our estimates suggest the implied costs are substantial in particular at the quarter-end when dealers' activity in the bond market falls as the cost of expanding their balance sheet increases due to regulation.

Recent empirical literature has explored the interactions between the PSPP and sovereign bond prices. Schlepper et al. (2020) find economically significant price impacts of the PSPP on German sovereign bonds using high-frequency inter-dealer data. They also document that transacting dealers update bond quotes rapidly, and the remaining dealers quickly follow suit, indicating that the Eurosystem is an important player in the German sovereign bond market.

Arrata et al. (2020) find economically significant price impacts of the PSPP on special repo rates, while De Santis and Holm-Hadulla (2020) find that the PSPP causes statistically significant and economically relevant temporary upward price impacts. Our paper, however, has a different focus and investigates the interaction between the design of the central bank purchase program (i.e., monthly targets) and the market structure in the euro area sovereign bond markets.

Several papers have documented surprising seasonal price patterns in bond markets. Most notably, Lou, Yan, and Zhang (2013) show that US Treasury yields typically rise ahead of US Treasury auctions. These price concessions result in extra profits for the dealers who get to buy bonds at slightly depressed prices in perfectly predictable and repeated US Treasury auctions. They are typically justified as 'fair' compensation for the warehousing risk faced by intermediaries with limited risk-bearing capacity who need to hold the newly issued US Treasuries while looking for a counterparty. The idea is similar to the traditional inventory risk explanation of bid-ask spreads (Stoll (1978)).

In our case, we observe an asymmetric pattern around large government bond purchases. This suggests that dealers get to sell bonds at slightly "overvalued" prices to the Eurosystem. Since arguably the Eurosystem is taking risk off the balance sheet of banks, it seems more difficult to explain why dealers should require extra compensation to reduce their interest rate risk exposure.[9]

[9] One possibility is that banks without Bund inventory need to enter a reverse repo transaction to obtain the bond in order to sell it to the Eurosystem. This may entail balance-sheet costs, which may affect dealers' ability to intermediate (He, Nagel, and Song (2021)). While this may be the case for some banks, in aggregate, European banks

Of course, arguably the Treasury bond warehousing risk faced by dealers could be effectively hedged using Treasury bond futures, which could somewhat mitigate the traditional explanation for the price concession. An alternative explanation for the price concession observed during bond issuances in the French government bond market is offered in Sigaux (2020), who argues that the price concessions are also compensation for the uncertainty faced by dealers about the amount to be issued. In our case, the purchased amount and target dates are public knowledge (i.e., the Eurosystem targets 60 and 80 billion euros in purchases by the end of every month during the PSPP).

Newman and Rierson (2004) document significant price concessions around large issuances in the European Telecom sector corporate bond market. They view these price concessions as compensation for warehousing risk faced by the dealers who absorb the issuance. They also document significant spillover effects to other bonds, interpreted as resulting from the overall lower risk-bearing capacity of bond dealers. Interestingly, we find that the effect is much more pronounced for the bonds that are targeted in a given day than for bonds that are perfect substitutes from a risk perspective but not purchased on a given day.

Our paper is also related to An and Song (2020), who show that dealers strategically manage inventory and charge uncompetitive pricing to the US Federal Reserve bank in the agency MBS market.

Also, our work has connections to Song and Zhu (2018), who document uncompetitive behavior among large dealers participating in the US Fed's QE auctions. Lastly, our findings about specific price patterns around Eurosystem purchases also resonate with the literature on 'slow-moving capital' (Duffie (2010)) or on 'inelastic markets' (Gabaix and Koijen (2021)), but the price patterns we find are unlikely to be driven by similar channels,[10]

Moreover, our findings are unlikely to be due to the 'adverse selection' channel of Kyle (1985) and Glosten and Milgrom (1985). Instead, we propose that the evidence is more consistent with a "non-competitive" market structure channel, whereby dealers exploit some of the features of the

hold a large amount of euro area sovereign bonds. This may, however, contribute to lowering competition around end-of-quarters, consistent with our findings.

[10] Duffie (2010) argues that inattention by some investors leads supply shocks to have persistent and lasting price effects in a competitive rational expectations (RE) model. Gabaix and Koijen (2021) argue that because some investors have some fixed mandates, the price impact of orders from unconstrained investors can have more dramatic 'permanent' price effects. Our findings are more of a temporary nature.

purchase program implementation.

Our results have two potential implications. First, the Eurosystem might consider moving away from committing to fixed purchase amounts at fixed dates. This concept was originally introduced to strengthen the perception that the ECB was determined in executing the PSPP when announced on 22 January 2015 (Rostagno et al. (2021)). The commitment to fulfill the mandate by each end-of-month under the PSPP can intensify the price pressure effect, granting more bargaining power to dealers towards each end-of-month. One approach could be to define the amount as a total envelope over a longer period, similar to the ECB's Pandemic Emergency Purchase Programme (PEPP).

Second, if the price pattern we identify is due to the non-competitive market structure as our model suggests, then the cost of the Eurosystem purchases are higher by a component that might be avoided by modifying the current purchase method. The Eurosystem could consider shifting towards trading on broader platforms open to a larger number of counterparties, to stimulate more competition from other natural sellers. Although some Eurosystem national central banks have used reverse auctions to target specific securities under the PSPP (Hammermann et al. (2019)), it might be beneficial to establish regular auctions possibly via some centralized electronic trading platform at the Eurosystem level. On this platform, all dealers, not limited to the national central bank's counterparties, could supply their available quantities for purchase by the Eurosystem. This platform could be opened to other large institutional investors (such as large insurance companies or mutual funds) who are the ultimate holders of these securities and might also be willing to trade their inventory of fixed-income securities. Such a system might also be beneficial in times of severe stress when the central bank may have to act as a 'buyer of last resort,' as recently advocated by Duffie (2020), in his review of the failures of the US Treasury market structure during the March 2020 Covid-crisis induced US Treasury market upheaval. Duffie's argument is that with reduced dealer balance sheet capacity and with increased supply of US Treasury bonds, in times of stress when international holders of US Treasuries may want to liquidate their position, dealers' warehousing capacity may be limited and the central bank may have to step in, acting as a buyer of last resort, to maintain secondary market liquidity in US Treasury securities. Our results suggest that having a regular and centralized auction mechanism for the Eurosystem to engage in large scale bond purchases might also be advantageous in normal times. Further analysis would be necessary to be more specific. Additionally, a cost-benefit analysis would be critical to assess such auction designs and their usefulness for the Eurosystem.

In the next section, we present some institutional details about the PSPP and its implementation and provide first evidence that the price anomaly can be linked to the PSPP. Then, we introduce a dynamic bargaining model that is consistent with the observed price pattern. Finally, we test additional implications of the model and discuss some of its implications for the implementation of large scale asset purchases in OTC markets.

2 Setting and data

2.1 Institutional background of the Eurosystem's quantitative easing programme

On January 22, 2015 the ECB announced its expanded asset purchase program (APP). The APP is part of a package of policy measures that was initiated in mid-2014 to support the monetary policy transmission mechanism and provide monetary stimulus in an environment where interest rates had fallen below zero.

The ECB governing council *ex ante* defined clear and observable monthly targets for how much to buy within a month.[11] Figure 1 illustrates the monthly volumes of the securities purchased under the APP. The continuous blue line shows the monthly target. Monthly purchases were conducted at an average pace of: 1) euro 60 billion from March 2015 until March 2016; 2) euro 80 billion from April 2016 until March 2017; 3) euro 60 billion from April 2017 to December 2017; 4) euro 30 billion from January 2018 to September 2018; and 5) euro 15 billion from October 2018 to December 2018.[12]

[11] In all months, the purchase guidance was expressed in monthly totals, rather than in strict daily volumes, providing flexibility in the day-to-day execution of purchases.

[12] On 12 September 2019 the ECB Governing Council decided that net purchases would be restarted under the APP at a monthly pace of euro 20 billion as of 1 November 2019.

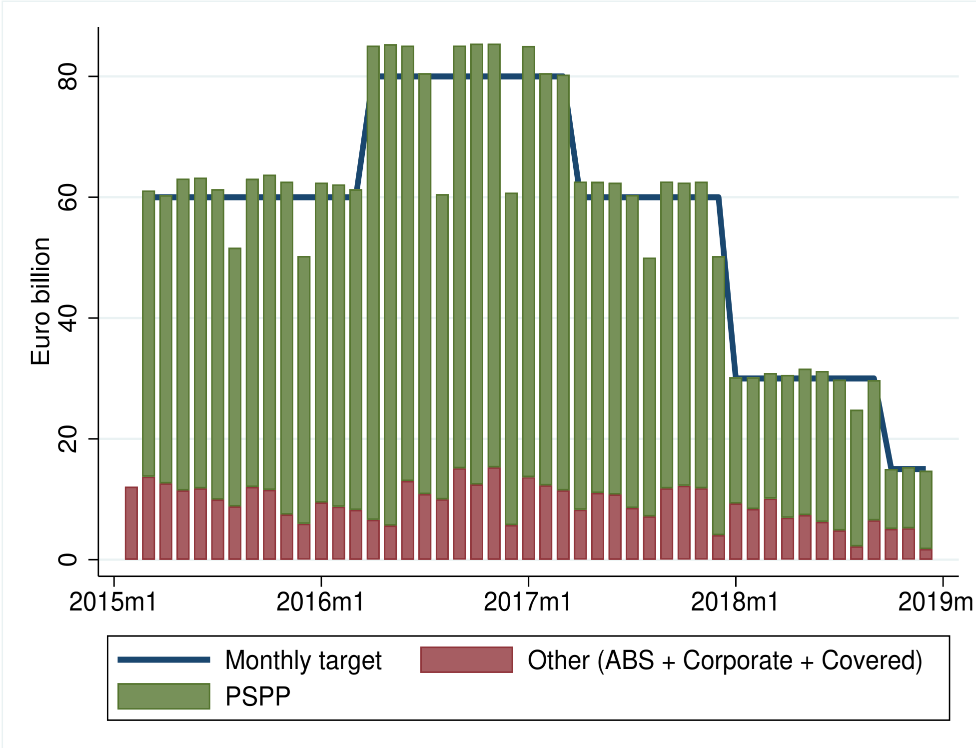


Figure 1. Average monthly purchases APP targets. Amounts in euro billions.

As shown in Figure 1, the amount of monthly purchases closely matches the average monthly APP purchase target. However, there are specific periods, such as from July to August and in December, when the purchase amounts fall below the target. During these periods, purchase activity is front and backloaded to account for seasonal patterns in fixed-income market activity, such as the decline in bond market liquidity. In addition, monthly fluctuations can reflect the variability in the redemption and reinvestment profiles as bond principal redemptions are reinvested in bonds issued by the same country and distributed over the calendar year.

The main component of the APP was the Public Sector Purchase Programme (PSPP) which accounts, on average, for almost 82% of the total net purchases (green bars in Figure 1).[13] The PSPP mainly targets bonds issued by euro area central governments, recognized agencies, and European institutions in the secondary market. The APP also includes the Corporate Sector Purchase Programme (CSPP), the Asset-Backed Securities Purchase Programme (ABSPP), and the Third Covered Bond Purchase Programme (CBPP3) (red bars in Figure 1). Although the

[13]Based on authors' calculation using public ECB data. See `https://www.ecb.europa.eu/mopo/implement/app/html/index.en.html`.

PSPP is coordinated by the ECB, it is implemented in a decentralized way both the ECB and the National Central Banks (NCBs). This means that most actual purchases are executed by the NCBs or by the ECB with their respective counterparties. When purchasing a bond, the executing central bank asks several - typically five - of its counterparties to provide one-sided quotes. The offer is accepted if at least three counterparties offer executable quotes, with the lowest price winning (see Hammermann et al. (2019)).

In this paper, we focus on the German sovereign bond market from March 9, 2015 and, to February 27, 2017 due to data availability and for the following reasons. Firstly, the German government debt is considered the "safe asset" in the euro area and is the most liquid sovereign bond (Corradin and Schwaab (2023)).

Secondly, a unique feature of the PSPP is that the allocation of purchases across countries is based on the ECB capital key (Hammermann et al. (2019), Bundesbank (2018)), with NCBs focusing exclusively on purchases in their home market. The Eurosystem adjusted its monthly PSPP amounts to align as closely as possible with a countrys share of the ECBs capital key. This implies that each country has a monthly target of purchase amounts as announced on January 22, 2015.[14] The ECB's capital key corresponds with the share of each member state in terms of total population and aggregated gross domestic product within the European Union (EU), with each of these two factors having equal weighting. As the largest economy and most populous country in the euro area, Germany has the highest ECB capital key and therefore has the largest allocation to the PSPP portfolio of approximately 26.3%, followed by France and Italy with a capital key of 20.7% and 18% respectively.

Figure 2 plots the monthly shares of purchases of German securities as part of the total PSPP purchases (represented by the continuous blue line), as well as Germany's share of the ECB's capital key (dashed red line) from 2015 to 2017. The data for this figure is derived from public information released monthly by the ECB when it discloses the country breakdown of purchases.[15],[16] The

[14] The ECB Governing Council decided that "*Purchases of securities under the expanded asset purchase programme that are not covered by the ABSPP or CBPP3 will be allocated across issuers from the various euro area countries on the basis of the ECB's capital key.*" See https://www.ecb.europa.eu/press/pr/date/2015/html/pr150122_1.en.html

[15] See https://www.ecb.europa.eu/mopo/implement/app/html/index.en.html.

[16] Market analysts frequently use the country breakdown data to compute the implied (or theoretical) monthly target at the country level or to determine deviations from the ECB capital key. For instance, refer to the BNP's report "ECB: The PSPP parameters" https://economic-research.bnpparibas.com/html/en-US/ECB-PSPP-parameters-9/23/2016,29112.

figure shows that the ECB capital key acts as a firm benchmark for Germany. The Eurosystem consistently purchased German securities each month, with the purchases approximating euro 17.25 billion when the total monthly target for the APP was euro 80 billion.[17] As such, the volume of purchases each month represents a consistent proportion of overall PSPP monthly purchases, and it aligns closely with Germany's share as dictated by the ECB capital key.

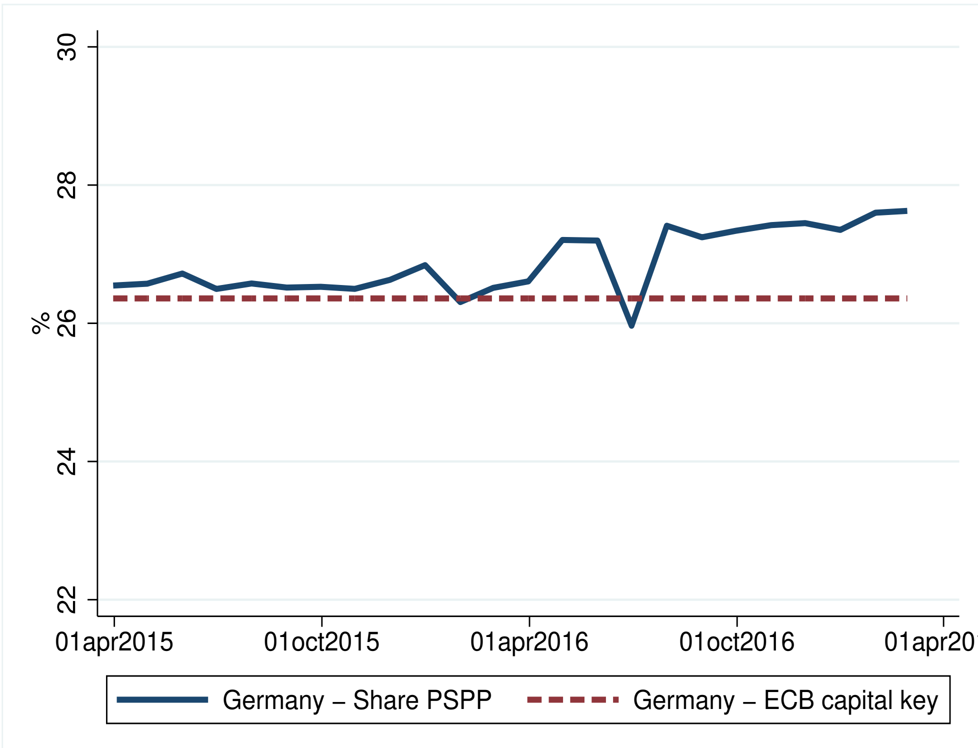


Figure 2. Monthly share of German securities purchased under the PSPP.

Thirdly, despite Germany being the largest economy within the EU, it does not have the largest sovereign bond market, and in fact, it carries a relatively low supply of debt. Prior to the start of the PSPP, Germany's central government bonds were valued at euro $1,398,475$ million. In contrast, France and Italy had a larger supply of central government bonds, with respective amounts of euro $1,695,039$ million and euro 2,112,558 million.[18] It is also worth noting that during our sample period, the net supply of German government bonds was negative, indicating that the volume of maturing bonds exceeded that of the newly issued ones. This dynamics potentially amplified the

[17] Considering that the PSPP accounts on average nearly 82% of all total net purchases, we calculate the figure as follows: euro 80 billion * 0.82 (PSPP share of total purchases) * 0.263 (Germany's capital key) = euro 17.25 billion.

[18] Refer to Eurostat government debt statistics `https://ec.europa.eu/eurostat/databrowser/view/gov_10q_ggdebt/default/table?lang=en`.

constraint on the available securities for purchase, thereby narrowing the scope of PSPP (Paret and Weber (2019)). As a result, the Eurosystem became the largest holder of German sovereign bonds within the euro area due to the PSPP, which was holding over 24% of the outstanding amount by the end of 2017 (Bundesbank (2018)).

The Eurosystem modified the PSPP parameters to address a potential shortage of public securities, particularly German ones. PSPP purchases are subject to a set of eligibility criteria. Initially, the PSPP initially included nominal and inflation-linked central government bonds. However, on December 3, 2015, marketable debt instruments issued by regional and local governments within the euro area were included as eligible assets.[19]. The expansion of eligible securities for the PSPP was intended to enhance the program's flexibility and facilitate its implementation (Schlepper et al. (2020)).

The PSPP initially specified that bonds to be purchased should have a maturity between 2 and 31 years. This range was broadened on January 19, 2017, when the minimum remaining maturity for eligible securities was lowered from two years to one year.

Furthermore, the total central bank holdings of a given security was capped at 33% (25%) of an issue (issuer).[20]. This limit was relaxed in September 2015, allowing the Eurosystem to hold up to 33% of an issuer.

Lastly, bonds purchased under the PSPP were required to have a yield above the ECB's deposit facility rate - the interest rate earned by banks when depositing money overnight with the central bank. On January 19, 2017, the ECB governing council eased this rule allowing additional bond purchases with yields below the deposit facility rate. This move restored eligibility for numerous German government bonds.[21]

Figure 3 shows the interesting dynamics of German sovereign yield distribution, displaying the mean, as well as the 25^{th} and 75^{th} percentile of the distribution. One immediately noticeable feature is the increasing proportion of German sovereign bonds with yields below the ECB deposit

[19] During the fourth quarter of 2015, the German central sovereign debt amounted to euro $1,372,200$ million, while the German general government debt - including regional and local debt was euro $2,178,095$ million. For more details, see `https://www.ecb.europa.eu/press/pressconf/2015/html/is151203.en.html`.

[20] Exceptions to the issuer limit could be made on a case-by-case basis.

[21] Specifically, *"With regard to the public sector purchase programme (PSPP), for each jurisdiction, priority will be given to purchases of assets with yields above the DFR. This implies that the amount of purchases that have to be made at yields below the DFR will fluctuate among jurisdictions, and may also change over time, reflecting market interest rate changes relative to the DFR."* See urlhttps://www.ecb.europa.eu/press/pr/date/2017/html/pr170119$_1$*.en.html*.

facility rate over time. At the start of the PSPP in March 2015, the ECB deposit facility rate was −0.2%, which was further decreased to −0.3% on 3 December 2015 and to −0.4% on 10 March 2016. Notably, while the average yield was considerably above the ECB deposit facility rate at the start of the PSPP, it even crossed the ECB deposit facility rate in the second half of 2016.

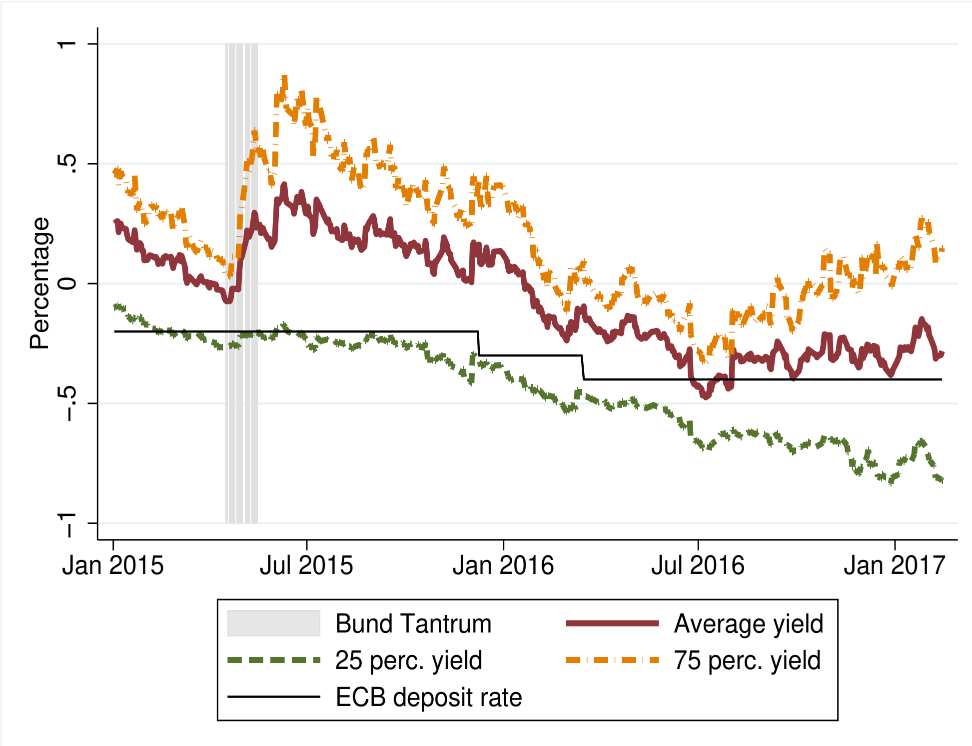


Figure 3. German sovereign yields.

Another notable feature of the German sovereign yields is their average decline, coupled with a significant increase in Spring 2015, as highlighted in Figure 3. This period, often referred to as the "Bund tantrum" (Bundesbank (2018), Riordan and Schrimpf (2015) and Scheicher and Schrimpf (2022)), saw average German sovereign yields reached the historical low of −0.024% on 28 April 2015. However, these yields then surged, increasing by almost 25 basis points within a week (by 6 May 2015). As demonstrated in Figure 3 (via the yellow dashed-dotted line), this spike is particularly striking for long-term bonds with higher yields.[22]

[22]Several factors could contribute to the overall yield increase for German bonds in Spring 2015. As part of a longer-term trend, bond market liquidity has been decreasing as dealers reduce their inventory holdings of fixed income assets. Some analysts have also suggested that the start of the ECB's PSPP early in 2015 might have further reduced the supply of tradable German bonds, a supply that had already been under pressure due to low issuance volumes in the primary markets.

2.2 Data

In this section, we outline the datasets used in our study and our approach to consolidating them into a comprehensive database for analysis.

We obtain bond characteristics data, such as time-to-maturity, and daily prices (yields) for sovereign bonds from Bloomberg. We make use of Bloomberg Generic quotes, which consist of single-security composites derived from electronic dealer contributions. Furthermore, we use Bloomberg CBBT quotes for price data.[23] We complement the price and volume data with Trax market data, which provides daily executed prices (low, mid, and high) and bid-ask quotes at bond level, along with monthly volumes. Trax is a global electronic bond trading platform that handles approximately 65% of all fixed income transactions in Europe.[24]

We rely on the ECB's Centralized Security Database (CSDB) for bond data characteristics. The CSDB contains information on all active debt securities issued in the euro area, providing static information on each bond such as country, coupon type (fixed, floating, or zero), outstanding amount, maturity date, and whether the issuer is a central government.

This data is merged with information on executed trades for the PSPP during the period from March 9, 2015 -, to February 27, 2017. These transactions are observed at the bond level and daily frequency. We have access to the amount purchased, the executed price, and information on whether the trade was executed by the ECB or a National Central Bank (NCB). Additionally, we know the identity of the counterparty.

Lastly, we incorporate special repo rates data from the Brokertec repo platform, which accounts for a significant share of German sovereign repo market transactions.[25] The dataset consists of intraday transactions, yet we derive daily observations by computing a volume-weighted average of the special repo rate during the day for each bond and repo maturity j.[26]

[23] CBBT is a real-time composite based on the most recently available executable contributions. It is designed to provide an accurate indication of where one can currently transact on Bloomberg Fixed Income Trading platform.

[24] Trax is the closest equivalent to FINRA's public trade tape in the US - Trade Reporting and Compliance Engine (TRACE). See page 5 of BlackRock's report `https://www.blackrock.com/corporate/literature/whitepaper/viewpoint-addressing-market-liquidity-euro-corporate-bond-market-2016.pdf`.

[25] There are two types of repo transactions: special repos and general collateral repos. In special repos, the party delivering the security must deliver a specific asset (with a specific ISIN code), while in general collateral repos (GC repos) he/she can choose among a basket of possible assets. Special repos imply the payment of a special rate. The special rate can be lower than the general repo rate, reflecting the convenience yield of the asset - how much sought-after the asset is.

[26] Our data contains transaction-level information recorded on a tick-by-tick basis, including the type of repo contract (either general collateral (GC) or special), the ISIN of the underlying government bond, the repo interest

Panel A of Table 1 provides the characteristics of the outstanding universe of German central sovereign bonds over our sample period (March 9, 2015 - February 27, 2017).[27] We report the mean and standard deviation computed at the bond-day level. The average maturity is 6.95 years, with an average yield (price) of -0.08% (117.69). Fixed-rate coupon bonds is approximately 85% of the share.[28] Some bonds are used in the repo market as collateral, and a vast majority of these bonds are issued by the German central government. The average special repo rate is -0.48%.

Table 1. Summary statistics

	Obs.	Mean	St.dev
Panel A - Outstanding universe			
Time-to-maturity (years)	27,918	6.95	7.40
Coupon rate (%)	27,918	2.26	1.94
Price	27,918	117.69	23.69
Yield	27,853	-0.08	0.55
Outstanding amount (euro mill.)	27,918	16,823	4,658
Dum. fixed rate coupon	27,918	0.85	0.35
Special repo rate (%)	27,354	-0.48	0.34
Panel B - PSPP eligibility			
Dum. eligible	27,918	0.47	0.50
Dum. eligible - deposit rate	27,918	0.50	0.50
Dum. eligible - time-to-maturity	27,918	0.70	0.46
Dum. ineligible - auction	27,918	0.02	0.16
Panel C - PSPP purchases			
Dum. purchase	27,918	0.27	0.44
Time-to-maturity (years)	7,417	11.61	7.69
Coupon rate (%)	7,417	2.87	1.88
Price	7,417	130.90	27.58
Yield	7,417	0.27	0.53
Outstanding amount (euro mill.)	7,417	17,844	3,916
Dum. fixed rate coupon	7,417	0.96	0.21
Special repo rate (%)	7,410	-0.47	0.28
Monthly cum. purchases / Outstanding (%)	772	1.69	1.39
Monthly cum. purchases / Trax volume (%)	685	11.92	12.10
Purchased amount	7,417	29.56	23.64
Num. counterparties	7,417	1.21	0.59

rate paid on each transaction, and the transaction volume. We consider three main repo maturities: i) overnight (ON), when the repo settles on the trade date T and the bond is repurchased on the next business day $T+1$; ii) tomorrow next (TN), when the repo settles at the trade date plus one business day $T+1$ and the bond is repurchased the following business day $T+2$; and iii) spot next (SN), when the repo settles at $T+2$ and the bond is repurchased at $T+3$.

[27] We only consider bonds for which we can observe a daily Bloomberg generic price (BGN).

[28] This share is computed using a dummy variable for each bond on a daily basis. Using the observed nominal outstanding amount, we obtain an average share of 87.49%.

Panel B presents statistics on the PSPP eligibility criteria. As mentioned earlier, a significant and distinctive feature of the PSPP is that securities must meet a set of eligibility requirements to be purchased. Over our sample period, on average, less than 50% of the German central sovereign securities were eligible for PSPP purchases. The main eligibility parameter affecting the eligibility share is the deposit rate rule: the yield of bonds must exceed the ECB deposit facility rate. As shown in Figure 3, the number of German sovereign bonds with a yield below the ECB deposit facility rate increased over time. The average yield was substantially above the ECB deposit facility rate at the start of the PSPP, but it approached and even dipped below the ECB deposit facility rate in the second half of 2016. Another significant eligibility parameter is the time-to-maturity: the bond must have a maturity of more than 2 years and less than 30 years. However, this rule largely coincides with the deposit rate rule: bonds with yields below the ECB deposit rate tend to be short and medium-term bonds. Lastly, a bond that is newly issued or reissued in an auction is not eligible for PSPP purchases and is subject to a blackout period (Arrata et al. (2020), De Santis and Holm-Hadulla (2020)).[29] On average, only 2% of our sample is affected by this rule.

Panel C provides details on the characteristics of the bonds purchased by the Eurosystem. Due to the PSPP eligibility criteria, the same bonds purchased through the PSPP program, on average, have a higher yield 0.27% and longer remaining maturity (11.61 years) compared to those not purchased. Moreover, these bonds have on average a higher coupon (2.87%) and a larger outstanding amount (€17,844 million). The purchases mainly consist of fixed rate coupon bonds (96%).[30]

To assess whether the Eurosystem purchases account for a large share of the trading activity, we first scale the monthly cumulative bond purchases with the corresponding outstanding amount. The Eurosystem buys almost 1.69% of the outstanding amount of German sovereign bonds each month on average. Then, we scale the monthly cumulative bond purchases with the monthly executed volume for the same bond by Trax.[31] For central government bonds, we observe that purchases account for 11.92% of the traded volume each month, suggesting that the Eurosystem is a large player in the German sovereign bond market. Finally, the average daily PSPP purchase amount of

[29]The data on auctions for German sovereign central debt are provided by the German Finance Agency.

[30]The purchases mainly consist of bonds issued by the central government (91% of the overall purchases) although our sample also includes regional and local bonds that became eligible on December 3, 2015.

[31]We limit our sample to bonds that are purchased within a month.

a bond is €29.56 million and the Eurosystem executes on average daily trades on the same bond with approximately one counterparty on average.

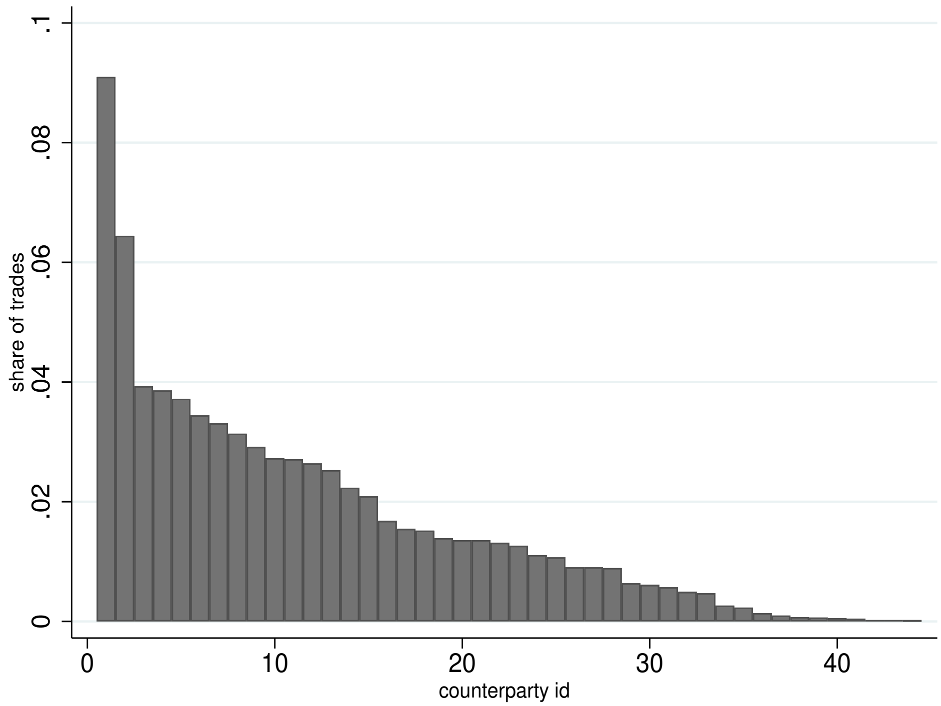
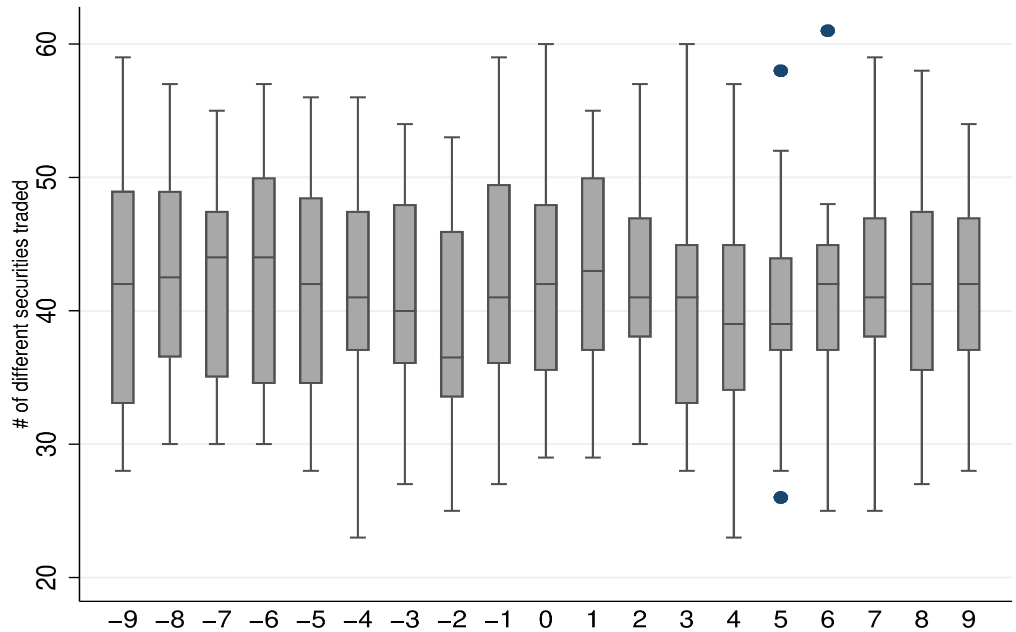


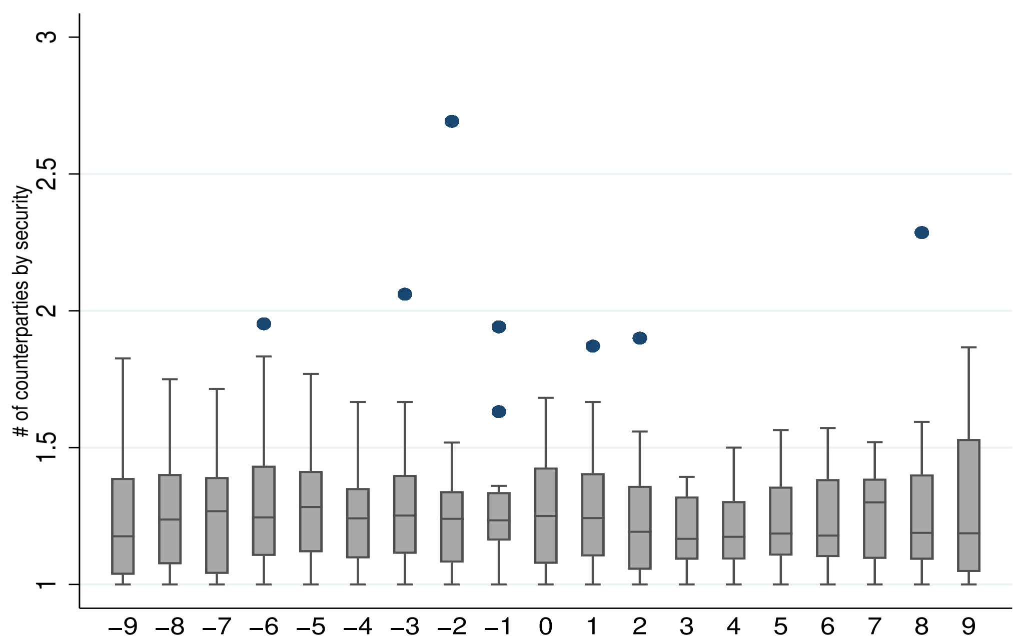
Figure 4. Dealer counterparty trading share. The figure plots the trading share for a given counterparty over the sample period March 15, 2015 to February 15, 2017.

There are around 40 counterparties with which the central bank interacts, with around 17 being active on a given trading day. The largest trader accounts for about 9% of all trades, followed by a trader with about 6% of trades. There are 15 traders that have a trading share larger than 2%. While some dealers naturally hold a larger share of trades, there seems to be a substantial number of traders taking significant portions of trades. The trading share of all dealers throughout our sample period is shown in Figure 4.

In Figure 5, we plot the number of distinct securities traded - in panel (a) - and the number of different traders for a given security - in panel (b) - around the end of each month (from 9 days before the end of the month to 9 days after the end of the month). On average, around 42 distinct securities are traded on a given day. While no specific pattern is particularly striking, the lowest average of distinct securities trades, around 35, occurs two days before the end of the month. The average number of traders trading a given security on a given day is about 1.3. Both of these



(a) Securities



(b) Counterparties

Figure 5. Dealer counterparty statistics.[Stefano: This figure has to be change between -8 and + 8 for consistency] The figure plots counterparty statistics. In panel (a) the number of different securities traded on a given day within the window is depicted. In panel (b) the number of different counterparties for a given security is shown.The sample period is from March 15, 2015 to February 15, 2017.

statistics suggest that the central bank interacts with dealers on different securities rather than executing multiple trades on one particular security.

3 The price anomaly

We follow the approach of Lou, Yan, and Zhang (2013) to analyse the time-series pattern in bond prices and yields around the end-of-month. For each bond, we use the price from 9 trading days before to 8 trading days after the end-of-month and compare them with the price on the beginning-of-window day that corresponds to the mid-of-month. That is, we track the same bond throughout the window around each end-of-month. Thus, for bond i we compute the time series of $\log(P_{i,j,t}/P_{i,j,-9})$ where $P_{i,j,t}$ is the price of the bond i at day t of window j (from -9 to 8) and $P_{i,j,8}$ is the price of the same bond on the end-of-window day ($t = 8$).

The pattern in sovereign prices around the end-of-month can be seen in the top panel of Figure 6. We plot the time series average of $\log(P_{i,j,t}/P_{i,j,-9})$ based on the regression

$$\log(P_{i,j,t}/P_{i,j,-9}) = \sum_{t=-9}^{T=8} \alpha_t \times \mathrm{D}_t + \epsilon_{i,j,t} \tag{1}$$

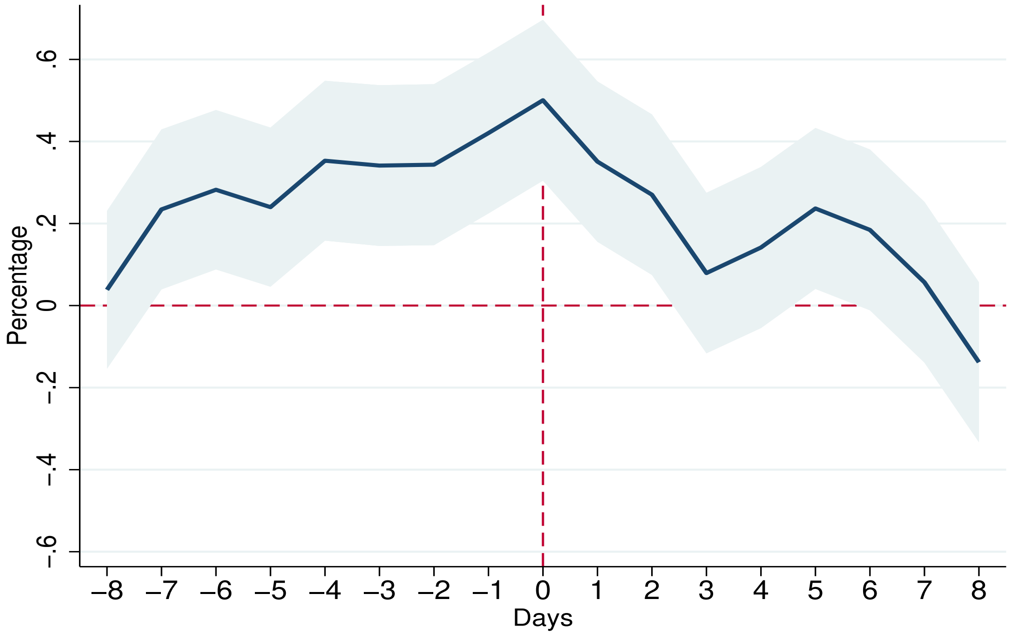
where D_t is a dummy variable that is equal to one on day t with t ranging from -9 to 8 (including $t = 0$), and $t = 0$ being the end-of-month day. Our sample includes fixed-rate coupon bonds issued by the German central government that are eligible for PSPP purchases.

We observe a clear asymmetric pattern: German sovereign bond prices show a consistent rise relative to the start of the window, only to experience a drop shortly thereafter. The bottom panel of Figure 6 shows this analysis, this time considering the yield distance $Y_{i,j,t} - Y_{i,j,-9}$. Here, $Y_{i,j,t}$ is the yield of bond i on day t within window j (from -9 to 8), and $Y_{i,j,-9}$ is the yield of the same bond on the start-of-window day ($t = -9$).

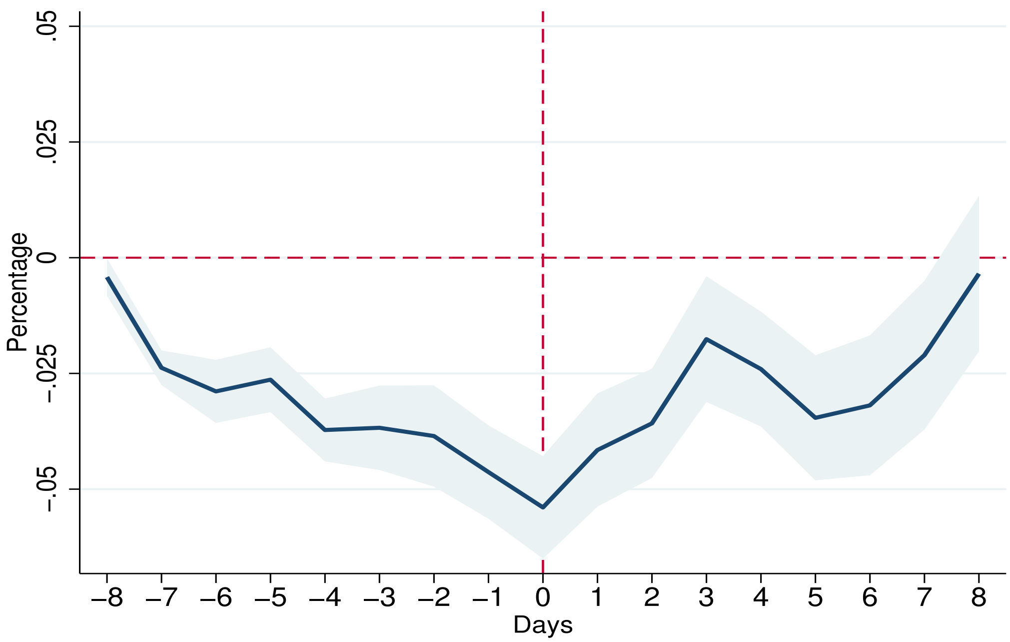
In this context, we observe a reverse asymmetric pattern: German sovereign bond yields depict a consistent decline relative to the start of the window, by approximately 5 bps, followed by a subsequent rise.[32]

Our estimates are of similar magnitude as the effects documented by Lou, Yan, and Zhang

[32] Figure 6 excludes the window of stark market movements in early May 2015 and includes end-of-quarter windows. Neither of these alter the results as shown in Figure A-I and Figure A-II.



(a) Holding returns



(b) Yield changes

Figure 6. Holding returns and yields of PSPP eligible bonds around end-of-month. The figure plots the coefficients α_t from the OLS regression. In panel (a) the dependent variable is $\log(P_t/P_{-9})$, where P_t is the price of the bond at day t. In panel (b) the dependent variable is $Y_t - Y_{-9}$, where Y_t is the yield on day t. The bond yields and prices are from BGN Bloomberg. t ranges from -9 to 8 (including $t = 0$) and $t = 0$ is the last day of the month. The main independent variable is daily indicator variables. Shadow area is 99%-confidence interval.

(2013), despite the stark contrast in the average yield levels of our sample at 0.27%. Their study uncovers a reverse V-shaped pattern in bond yields: US Treasury security yields in the secondary market experienced a significant surge a few days prior to Treasury auctions and subsequently decline. They report, for instance, that the yield on 2−year US Treasury notes increases on average by 2.53 bps during the five-day period leading up to the auction and then decreases by 2.32 bps over the subsequent five-day period. However, it is worth noting that the average yield in their sample, spanning from January 1980 to June 2008 ranges from 6.36% (2−year notes) to 7.57% (10−year notes).

In the estimation of Equation (1), we exclude the "Bund tantrum" window (April 15 - May 15, 2015) due to the unprecedented move in yields around that period. However, our main finding of the consistent rise and subsequent fall in German sovereign bond prices relative to the beginning of the window remains unaltered by this exclusion, as will be shown later. When we compute the window, we exclude public holidays and end-of-year windows because the Eurosystem does not actively buy securities in the second half of December. We also insist on a balanced panel structure, where all individual bond observations observable for every time period within the window. While these conditions do limit our sample size, the impact on our sample is only modestly affected (Table A-I).

Table 2 reports the main results for holding returns, while Table A-II in the Appendix shows the corresponding findings for yields. We control for bond times window fixed effects while re-estimating our regression specification to account for changes in bond market conditions at the bond level. We use standard errors clustered at the bond times window level and find that all coefficients are almost unchanged relative to those in Figure 6, with the coefficients on the dummy D_t for days ranging from -9 to 0 remain statistically significant at the 1% level (Column (1)).

Then, we report our estimates for German sovereign bonds that were ineligible for PSPP purchases in Column (7).As discussed in Section 2.1, a key and distinctive feature of the PSPP is the necessity for purchased securities to meet certain eligibility criteria. As documented in Panel B of Table 1, on average more than 50% of the German central sovereign securities were ineligible for PSPP purchases over our sample period. We observe no steady increase (decrease) in bond prices (yields) relative to the start of the window nor a subsequent drop (rise) for these bonds. Moreover, our estimates do not suggest any alternative pattern because all the coefficients are statistically insignificant. Overall, our findings provide first evidence linking the price anomaly to the PSPP.

Another way to interpret the results is by estimating our main specification for different maturity buckets while pooling PSPP eligible and ineligible bonds (see Table A-III in the Appendix). We use the following breakdown by maturity buckets: less than two years, two to five years, five to ten years, ten to twenty years and more than twenty years. The asymmetric pattern previously documented is clearly present only for the five to ten years, the ten to twenty years and more than twenty years maturity bucket. . This is mainly attributed to the PSPP eligibility criteria. First, German sovereign bonds with a time-to-maturity less than two years were ineligible for PSPP purchases.[33] Second, more short-term German sovereign bonds, with maturity up to five years carried negative yields and traded below the ECB deposit rate, thereby becoming ineligible for PSPP purchases.

[33]The maturity range of the PSPP was broadened by decreasing the minimum remaining maturity for eligible securities from two years to one year on January 19, 2017, at the end of our sample period.

Table 2. Bond holding returns around the end-of-month - This table presents the coefficients from a regression analysis, where the dependent variable represents bond holding returns, calculated as the logarithmic ratio of bond price $P_{i,j,t}$ to $P_{i,j,-9}$. Here, $P_{i,j,t}$ refers to the price of bond i on day t within window j (ranging from -9 to 8), and $P_{i,j,-9}$ signifies the price of the same bond on the final day of the window (i.e., $t = -9$). The independent variable is day t, which spans from -9 to 8, including $t = 0$, which represents the month's end. The regression model incorporates bond-window specific fixed effects, and standard errors are clustered at the bond-window level. Standard errors are bracketed. Significance levels are denoted as follows: $***$ for 1%, $**$ for 5%, and $*$ for 10%.

	(1)	(2)	(3)	(4) PSPP eligible	(5)	(6)	(7) PSPP ineligible
	Base	Without quarter-end	Repo adjusted	Without newly issued bonds	Without benchmark bonds	With Bund tantrum	
-8	0.037*	-0.070***	0.038*	0.041*	0.040*	0.051**	0.013
-7	0.221***	0.157***	0.224***	0.223***	0.222***	0.212***	0.016
-6	0.270***	0.214***	0.273***	0.274***	0.271***	0.223***	0.052***
-5	0.253***	0.204***	0.257***	0.246***	0.242***	0.200***	0.002
-4	0.364***	0.227***	0.370***	0.361***	0.360***	0.307***	0.005
-3	0.347***	0.193***	0.354***	0.349***	0.351***	0.288***	-0.007
-2	0.351***	0.181***	0.359***	0.356***	0.358***	0.289***	0.019
-1	0.411***	0.194***	0.421***	0.419***	0.419***	0.277***	0.012
0	0.496***	0.286***	0.506***	0.496***	0.495***	0.316***	0.044
1	0.344***	0.092	0.356***	0.344***	0.342***	0.168**	-0.016
2	0.261***	-0.005	0.274***	0.261***	0.256***	0.018	-0.014
3	0.072	-0.270***	0.086	0.066	0.060	-0.206**	-0.030
4	0.136**	-0.167**	0.151**	0.132**	0.127**	-0.141	-0.004
5	0.232***	-0.121*	0.248***	0.227***	0.220***	-0.034	0.008
6	0.179**	-0.158*	0.197**	0.170**	0.162**	-0.120	0.047
7	0.056	-0.259**	0.075	0.051	0.040	-0.253**	0.027
8	-0.147	-0.330***	-0.127	-0.147	-0.160*	-0.467***	-0.018
Obs.	9,769	7,244	9,769	9,520	9,518	10,431	8,933
R^2	0.5429	0.4630	0.5429	0.5429	0.5421	0.5886	0.6053

We now turn to address potential concerns with the pattern observed for PSPP-eligible bonds in Columns (2)-(6). First, we repeat our analysis restricting our sample excluding the end-of-quarter windows (Column (2)). Recent empirical literature documents that the introduction of the Basel III leverage ratio regulation has had "window-dressing" effects on bond markets at quarter-ends (Munyan (2017)). We find that the results are qualitatively similar to the ones reported for the full sample. The coefficients are about a third smaller than those in specifications with quarter-end windows. However, these results continue to remain statistically significant at the 1% level over the period before the end of the month.

Existing literature has argued that dealer activity in the bond market falls significantly around quarterend, as the cost of expanding their balance sheet increases (Arrata et al. (2020), Corradin et al. (2020), and Breckenfelder and Ivashina (2021)).[34] This seems to amplify the pattern we identify. Within our model's framework, this can be explained by a reduction in competition among dealers to provide an executable quote around quarter end.[35]

Second, another potential concern with our return pattern is the variation in repo funding costs around the end-of-month. To address this, we repeat our analysis in Column (3), but this time we now adjust for repo funding costs when computing holding returns. Specifically, we subtract the cumulative special repo rates for the same bond scaled by 1/360 from the bond holding return.[36] Our main results are unaffected by this adjustment.

Third, there might be concerns that the pattern we uncover is affected by issuance activity. If new bonds are issued at the end-of-month, then issuance may create an upward price pressure on newly issued bonds driving our results. To address this issue, we repeat our analysis in Column (4) excluding newly issued bonds within a window. We find that all coefficients are almost unchanged relative to Column (1).

Fourth, a potential concern is that the pattern could be attributed to temporary spikes in investor demand for specific securities due to index rebalancing. To address this concern, we

[34] This recent literature documents that the Basel III leverage ratio regulation affects repo market activities. The leverage ratio is a non-risk weighted measure that requires banks to hold capital in proportion to their overall balance sheet size. Repos expand a bank's balance sheet and therefore attract a capital charge under the leverage ratio. As the margin on repos is low, a binding leverage ratio makes it more costly for banks to engage in repo compared to engaging in activities with higher margins (but equal capital charge), providing them with an incentive to reduce their activity (see also Duffie and Krishnamurthy (2016) and Duffie (2018)).

[35] This could also be related to the fact that repo rates increase around quarter end making it more costly for dealers to sell a bond if they do not already have it in their inventory.

[36] We use the spot next special repo rates.

exclude bonds entering the Bloomberg Germany Treasury Bond Index within a window (Column (5)).[37] Our main results are unaffected by this exclusion.

Finally, we repeat our analysis including the "Bund tantrum" window (Column (6)). Our estimates confirm the general pattern that bond prices of German sovereign bonds eligible for PSPP purchases steadily increase relative to the beginning of the window and drop shortly after.

In Table A-IV of the Appendix, we provide further robustness analysis. First, the documented price pattern around the end-of-month is not unique to Bloomberg BGN quotes. We re-estimate our main specification using Bloomberg CBBT quotes, Eurosystem executed prices and Trax traded prices to compute the holding return. We find that all coefficients remain statistically significant at the 1% level when we look at the nine days period before the end-of-month. Overall, Bloomberg quoted and Trax traded prices are aligned. Our results are consistent with Schlepper et al. (2020) who investigate the price impact of the PSPP on German sovereign bonds using minute-by-minute frequency MTS data. They document that transacting dealers quickly update bond quotes in the MTS market and the remaining dealers quickly follow.

4 The model

We propose a simple search-bargaining model of the Eurosystem purchases to explain qualitatively the price pattern observed in the data. We first assume the central bank wants to purchase 1 unit of bond from N dealers (we consider multiple units below). We assume each dealer will be contacted and quote a bond price with probability $\eta < 1$. This can be justified by (i) a cost of searching too many dealers, (ii) an operational cost for dealers to always be present in the market at all time to respond to an inquiry, (iii) the potential lack of inventory in the specific bond at a particular dealer when contacted by the bank perhaps because it was just sold to another client, or a combination of these. We note that it is straightforward to let η depend on the round of trading.[38]

We assume that there are T rounds of trading for the bank to buy from the dealers and that

[37] This index is used as a benchmark index for Bund ETFs such as the iShares Germany Government Bond ETF.

[38] Alternatively, we can think of η as the exogenous probability with which the bank chooses to contact a given dealer. Why would the bank not contact all dealers in every round? Perhaps because it considers that process too costly. Note that in the implementation of the PSPP, as described in section 2.1, the Eurosystem requires a minimum of 3 quotes from 3 different dealers. One might think this could be sufficient for Bertrand competition to kick in. However, in reality, it is plausible that some of the contacted dealers give relatively wide quotes if they do not have the asset in inventory and anticipate a costly reverse repo transaction to obtain the asset. An interesting extension for future research would be to endogenize the choice of η by dealers.

the maximum value the bank is willing to pay for one unit in the final round is v. The cost to the dealers is assumed to be 0.[39] So v is the 'excess' premium the bank is willing to pay over and above the 'fair price' to fill its mandate of acquiring 1 bond in the market. We assume dealers and bank try to maximize the expected gains from trading.

We assume symmetric strategies equilibrium for all dealers who are ex-ante identical. We consider an equilibrium where dealers follow mixed strategies and quote according to a continuous density with cumulative distribution function $H_t(p)$ in round t. The equilibrium price quote density can be derived recursively. Let's start in the last period $t = T$. Conditional on quoting a price, a dealer will be indifferent between any p, drawn from $H_T(p)$ defined on $[\underline{p}_T, \overline{p}_T]$, if and only if she gets the same expected gain at every price. The maximum price the bank is willing to accept in the last period is v, therefore $\overline{p}_T = v$. If the dealer quotes v her expected profit is $(1-\eta)^{N-1}v$, that is she earns v only if she is the only dealer to quote a price in that period (which happens with probability $(1-\eta)^{N-1}$), because if any other dealer is contacted, since dealers quote from a continuous density, with probability 1 there will be a lower price available in the market, which will be preferred by the bank. Now, if the dealer quotes another price $p \in [\underline{p}_T, v)$ then her expected profit is $p \sum_{k=0}^{N-1} C_{N-1}^k \eta^k (1-\eta)^{N-1-k}(1-H_T(p))^k$. That is she gets p only if the k other dealers, that are present with probability $C_{N-1}^k \eta^k (1-\eta)^{N-1-k}$, quote a price that is greater than p, which occurs with probability $(1-H_T(p))^k$.[40]

The indifference condition then allows to deduct the equilibrium density. For all $p \in [\underline{p}_T, \overline{p}_T]$ we have:

$$p \sum_{k=0}^{N-1} C_{N-1}^k \eta^k (1-\eta)^{N-1-k} (1-H_T(p))^k = v(1-\eta)^{N-1} \tag{2}$$

The lower bound $\underline{p}_T$ is the lowest value such that $H_T(\underline{p}) = 0$.

Now, we can derive the equilibrium quoting density in every round recursively. To that effect, suppose that we have $H_{t+1}(p) : [\underline{p}_{t+1}, \overline{p}_{t+1}] \to [0,1]$ the density with which dealers quote in round $t+1$. Then consider the optimal quoting behavior of a dealer at date t. Again she will quote optimally from a continuous density $H_t(p)$ so as to get the same expected gain for every quoted price in equilibrium. Similarly to what happens at date T, we have the following indifference

[39] It is straightforward to extend to any fixed cost $c < v$ by simply redefining v.

[40] We use the standard notation for the binomial coefficient $C_n^k = \frac{n!}{k!(n-k)!}$.

condition which determines the density for any price $p \in [\underline{p}_t, \overline{p}_t]$:

$$p \sum_{k=0}^{N-1} C_{N-1}^k \eta^k (1-\eta)^{N-1-k} (1 - H_t(p))^k = \overline{p}_t (1-\eta)^{N-1} \tag{3}$$

We can use Euler's binomial formula to simplify this equation to:

$$p \left(1 - \eta H_t(p)\right)^{N-1} = \overline{p}_t (1-\eta)^{N-1}$$

It follows that $\forall t$ the quoting density is:

$$H_t(p) = \frac{1}{\eta} + (1 - \frac{1}{\eta}) \left(\frac{\overline{p}_t}{p}\right)^{\frac{1}{N-1}} \tag{4}$$

The lower integration bound is found by solving $H_t(\underline{p}_t) = 0$:

$$\underline{p}_t = \overline{p}_t (1-\eta)^{N-1} \tag{5}$$

This has a nice interpretation: if a dealer quotes the lowest price, she will sell with probability one, and in expectation earn the same expected revenue as when she quotes the highest price, in which case she sells if she is the only one making a market (with probability $(1-\eta)^{N-1}$).

Thus we can compute the average price quoted by dealers (conditional on quoting) in every round:

$$p_t^a = \int_{\underline{p}_t}^{\overline{p}_t} p \, dH_t(p) = [pH_t(p)]_{\underline{p}_t}^{\overline{p}_t} - \int_{\underline{p}_t}^{\overline{p}_t} H_t(p) \, dp \tag{6}$$

$$= \overline{p}_t \gamma_N \tag{7}$$

$$\gamma_N = \begin{cases} \frac{(1-\eta)(1-(1-\eta)^{N-2})}{\eta(N-2)} & \text{if} \quad N > 2 \\ (1 - \frac{1}{\eta}) \log(1-\eta) & \text{if} \quad N = 2 \end{cases} \tag{8}$$

Similarly, we can compute various moments of the quoted price distribution.

It remains to identify the upper integration bound $\overline{p}_t$. What is the highest price the bank will be willing to accept in round t? It should be the highest price at which the bank becomes indifferent between trading now or continuing to the next round. We define the upper reservation price recursively by noting that in the last trading round $\overline{p}_T = v$ (which gives a trading surplus of $s = v - \overline{p}_T = 0$). At $T-1$, the upper reservation price will be such that $v - \overline{p}_{T-1} = \beta\{\mathbb{E}[\hat{s}_T]\}$, where we define the maximum surplus that the bank can obtain if she trades in round t by

$$\hat{s}_t = \max[s_t^1, \ldots, s_t^N], \tag{9}$$

and where we define the surplus from transacting with dealer i by $s_t^i = v - p_t^i$ if dealer i quotes a price in round t and $s_t^i = 0$ otherwise. We also allow for a discount factor $\beta \in [0,1]$ to reflect the bank's impatience or rate of time preference.[41]

Similarly, in every round $t < T$ we obtain the upper reservation price recursively by solving:

$$v - \overline{p}_t = \beta\{\mathbb{E}[\hat{s}_{t+1} + \mathbf{1}_{\hat{s}_{t+1}=0}(v - \overline{p}_{t+1})] \tag{10}$$

It remains to derive the distribution of $\hat{s}_t$. To that effect we note that for any $v - p > 0$:

$$\hat{H}(v-p) := Prob(\hat{s} \leq v-p) = Prob(s^1 \leq v-p, \ldots, s^N \leq v-p) \tag{11}$$

$$= (1 - \eta + \eta(1 - H(p)))^N \tag{12}$$

$$= (1 - \eta H(p))^N \tag{13}$$

$$= (1-\eta)^N (\frac{\overline{p}}{p})^{\frac{N}{N-1}} \tag{14}$$

[41] Note that we implicitly assume that the bank always buys at the lowest price quoted to her in any round. Actually, this is also the optimal strategy for the bank, since given the definition of the upper reservation price, it is never optimal to wait to buy later. So in the case where the bank seeks to buy only 1 asset, she would actually purchase the asset the first time a dealer quotes an 'executable' quote to her. Since the probability of a trade in a given round is $p^{trade} = 1 - (1-\eta)^N$, then on average the first trade would be expected to occur at time $\tau = 1/p^{trade}$.

We can then compute the expected surplus:

$$\mathbb{E}[\hat{s}] = -\int_{\underline{p}}^{\overline{p}} (v-p) d\hat{H}(v-p) \tag{15}$$

$$= -[(v-p)(1-\eta H(p))^N]_{\underline{p}}^{\overline{p}} - \int_{\underline{p}}^{\overline{p}} (1-\eta H(p))^N \, dp \tag{16}$$

$$= v - \underline{p} - (v-\overline{p})(1-\eta)^N - (1-\eta)^N \int_{\underline{p}}^{\overline{p}} (\frac{\overline{p}}{p})^{\frac{N}{N-1}} \, dp \tag{17}$$

$$= v(1-(1-\eta)^N) - \overline{p}N\eta(1-\eta)^{N-1} \tag{18}$$

$$\tag{19}$$

We have now characterized the problem and obtained a recursive solution. Let's summarize our results on the equilibrium price quote density in any round t: $H_t(p) : [\underline{p}_t, \overline{p}_t] \to [0,1]$:

$$H_t(p) = \frac{1}{\eta} - \frac{(1-\eta)}{\eta}(\frac{\overline{p}_t}{p})^{\frac{1}{N-1}} \tag{20}$$

$$\underline{p}_t = \overline{p}_t(1-\eta)^{N-1} \tag{21}$$

$$\overline{p}_T = v \tag{22}$$

$$v - \overline{p}_t = \beta\left\{v - \overline{p}_{t+1}(1-\eta)^{N-1}(1+(N-1)\eta)\right\} \;\; \forall t < T \tag{23}$$

$$\mathbb{E}[\hat{s}_t] = v(1-(1-\eta)^N) - \overline{p}_t N\eta(1-\eta)^{N-1} \tag{24}$$

Note that if there is no discounting ($\beta = 1$) then the recursion for the upper reservation price simplifies to:

$$\overline{p}_t = (1-\eta)^{N-1}(1+(N-1)\eta)\overline{p}_{t+1} \tag{25}$$

$$= (1+(N-1)\eta)\underline{p}_{t+1} \;\; \forall t < T \tag{26}$$

Clearly, in that case, the trading range increases at a geometric rate at each trading round. Thus, the average price at which we expect the transaction to occur increases towards maturity. As we approach maturity, dealers recognize that they have more bargaining power (as they are less likely to face competition from dealers in future rounds) and thus quote higher prices. This intuition holds for the more general case with $\beta < 1$, as we illustrate in figure 7 below. The earlier the bank can trade the higher the expected surplus. The expected surplus of the bank drops towards maturity, and the drop is more severe the less competition dealers face, that is the smaller is $N\eta$, and the more impatient the bank is, that is the lower is β.

As we show in panel (c) and (d), if the degree of competition among dealers is very high (here $\eta = 0.5$, which implies that on average 5 dealers quote a price in every round), then the trading range is approximately constant over the trading horizon and concentrated close to zero (except for the last trading round where the upper end of the range is by definition $\overline{p}_T = v \equiv 1$). With high competition, the bank earns all the surplus and we can see in panel (d) that the expected surplus of the bank's trade is approximately constant and equal to 1. That is, with high competition the bank expects to pay a price close to 0 in every trading round and to extract the full surplus. Instead, with low competition as illustrated in panel (a) and (b) then the trading price is expected to increase significantly as we approach maturity and the bank's expected surplus of a trade decreases severely the closer to maturity she trades.

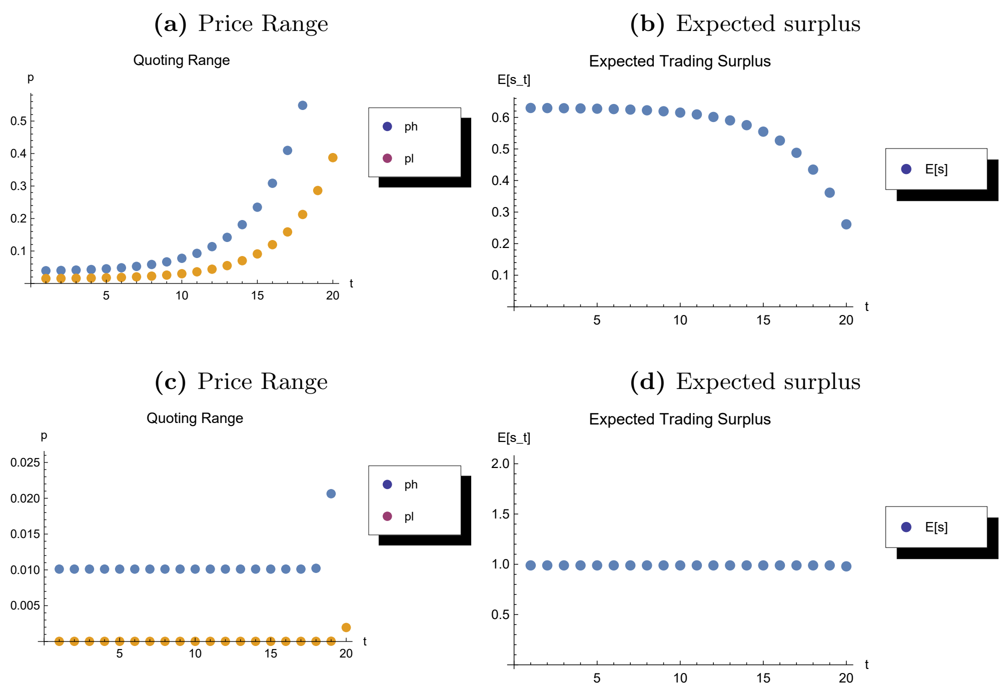
The figure above characterises the expected trading price when the bank seeks to buy one unit over multiple rounds. In practice the bank seeks to purchase several units. We turn to that case next.

4.1 Purchasing Multiple Units in one round

We now consider the case where the bank wants to buy several units, e.g., $U \geq 1$ by contacting N dealers who each can sell only one unit when contacted. As before we assume that dealers quote a price for that unit with probability η.

Consider first the final trading round. Clearly, if the number of units that the bank still wants to purchase is $U > N$, then every contacted dealer knows that she is not in competition with any other dealer and thus will quote a price of $p_T = v$, the reservation price of the bank. Instead, if $U < N$, then dealers will quote from a continuous distribution $H(p) : [\underline{p}, \overline{p}] \rightarrow [0, 1]$, so as to be indifferent between every price. The maximum price $\overline{p} = v$ will be received only if there are at most $U - 1$ dealers who quote a price among the remaining $N - 1$ dealers. Instead, if the dealer quotes a price $p < v$, then the bank will buy at that price if among all other dealers, who quote a price, at most $U - 1$ quote a lower price. It is helpful to define $\hat{s}^i_N$ to be the i^{th} largest order

Figure 7. Model illustration Panel (a) shows the lower and upper prices of the quoting range $[\underline{p}_t, \overline{p}_t]$. Panel (b) shows the unconditional expected trading surplus $E[\hat{s}_t]$ obtained from trading in various rounds as a function of time $t \in [0, T = 20]$ for a value of $\eta = 0.1$, $\beta = 0.99$, $N = 10$, and $v = 1$. Panels (c) and (d) show the quoting range and expected trading surplus for a higher $\eta = 0.5$, which implies a high degree of competition among dealers in every round.



statistic among a set of N i.i.d. random variables $s^1, \ldots, s^N$, where the $s^i = (v - p^i)\psi^i$ where the p^i are drawn from the distribution $H(p)$ and the ψ^i are binomial equal to 1 with probability η and 0 else. With this notation we can define the indifference condition in the final round as follows:

$$v\,Prob(\hat{s}^U_{N-1} \leq 0) = p\,Prob(\hat{s}^U_{N-1} \leq v - p) \tag{27}$$

Note that by definition of the order statistic (the u-highest r.v. in a set of n iid r.v. is smaller than α iff at most $u-1$ r.v. selected in the set are higher than α), we have

$$Prob(\hat{s}^u_n \leq v - p) = \sum_{k=0}^{u-1} C^k_n (\eta\,H(p))^k (1 - \eta\,H(p))^{n-k} \tag{28}$$

It follows that the indifference condition can be rewritten as:

$$v \sum_{k=0}^{U-1} C^k_{N-1} \eta^k (1-\eta)^{N-1-k} = p \sum_{k=0}^{U-1} C^k_{N-1} (\eta\,H(p))^k (1 - \eta\,H(p))^{N-1-k} \tag{29}$$

This equation can be solved for the equilibrium quoting density $H_{T,U}(p)$. We see that the indifference condition reduces to the one unit solution derived in the previous round when $U = 1$ (i.e., when the bank has only one remaining unit to buy in the final round). Since we were not able to get an explicit solution for $H(p)$ we solve this equation numerically.

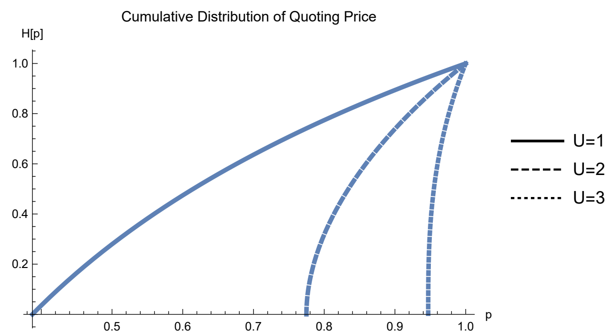
Finally, the lowest quoting price $\underline{p}$ can be found by solving for $H(\underline{p}) = 0$. Note that the equation above then implies the value for $\underline{p}$ satisfies:

$$\underline{p}_{T,U} = v \sum_{k=0}^{U-1} C^k_{N-1} \eta^k (1-\eta)^{N-1-k} \tag{30}$$

which states that the expected profit obtained by quoting the lowest value and getting a trade with probability 1 is equal to the expected profit of quoting the highest possible value and getting exercised only if no one else is quoting.

Figure 8 below shows the cumulative distribution function $H_{T,U}(p)$ in the final round T, when there are U units remaining to be purchased, for various values of $U \in \{1, 2, 3\}$. We see that as there are more units to be purchased the distribution function shifts to the right, that is $H_{T,1}(p) \geq H_{T,2}(p) \geq H_{T,3}(p)$, which reflects the fact that, all else equal, dealers have an incentive to quote higher prices in the final round, the more units the bank has to purchase to achieve its target. In turn, the bank's incentive is to buy in previous rounds to reduce the dealers' market power in the last round. We solve for the banks optimal bidding strategy in previous rounds next.

Figure 8. Quoting distribution in the final round $H_{T,U}(p)$ when bank still needs to purchase U units from N dealers, for $\eta = 0.3$, $N = 10$, and $v = 1$.



4.2 Purchasing multiple units over several trading rounds

Now we consider the case where the bank can spread the purchase of the U bonds across several T trading rounds. For simplicity we assume the bank can buy at most one unit per round in every round except the last round T, where she can buy as many units required to fill her objective.[42] We further assume that in each round it is common-knowledge among the dealers how many units the Bank has bought, and therefore how many remain to be purchased. We define $H_{t,u}(p)$ the equilibrium quoting density for dealers in round t when the Bank has a total remaining objective of u units to buy (she therefore bought $U - u$ units in rounds prior to t). Since in round t the bank is contacting dealers to buy one unit, the quoting density satisfies the following indifference condition (similar to the one unit case studied before hand):

$$\overline{p}_{t,u}(1-\eta)^{N-1} = p \sum_{k=0}^{N-1} C_{N-1}^{k} \eta^{k} (1-\eta)^{N-1-k} (1 - H_{t,u}(p))^{k} \tag{31}$$

$$= p(1 - \eta H_{t,u}(p))^{N-1} \tag{32}$$

[42]It could be interesting to consider richer strategies where the bank can buy possibly multiple units from one bank or buy one unit from several banks in each round, depending on the various quotes obtained. We leave this for future research. Note that the present simplifying assumption is consistent with the implementation strategy of PSPP by the Eurosystem, who requests quotes from multiple dealers for every, standard size notional, bond trade.

from which we obtain the density. Further, the minimum price a dealer will be willing to quote will satisfy:

$$\underline{p}_{t,u} = \overline{p}_{t,u}(1-\eta)^{N-1} \tag{33}$$

Together we obtain the explicit solution as in equation 4

$$H_{t,u}(p) = \frac{1}{\eta} - \frac{(1-\eta)}{\eta}(\frac{\overline{p}_{t,u}}{p})^{\frac{1}{N-1}} \tag{34}$$

It remains to compute the maximum price the bank will be willing to pay in a given round $\overline{p}_{t,u}$ when she has still $u \geq 1$ units to purchase prior to T. This value will be such that the bank is indifferent between buying one unit now at the smallest of all quoted prices or delaying the purchase to the future. Specifically, we will construct the upper reservation price recursively. In the last round, clearly $\overline{p}_{T,u} = v \ \forall u \geq 1$. For the previous rounds, it is useful to define the expected value at time t of future surpluses to the bank who still needs to acquire u units, $J(t,u)$. We define it recursively.

$$J(T,u) = \mathbb{E}[\hat{s}^1_{T,u} + \ldots + \hat{s}^u_{T,u}] \ \forall u > 0 \tag{35}$$

$$J(t,u) = \mathbb{E}[\hat{s}^1_{t,u}] + \beta(1-(1-\eta)^N)J(t+1,u-1) + \beta(1-\eta)^N J(t+1,u) \ \forall u > 0 \text{ and } \forall t < T \tag{36}$$

The first equation states that in the last round if the bank still has u units to buy she gets the expected surplus of the u highest order statistics. The second equation says that if in a previous round t she has still u units to buy then the expected surplus is the expected surplus of the lowest price quoted in this round plus the expected discounted surplus from purchasing $u-1$ units in future rounds if a trade occurred in this round, or u units otherwise.[43]

Then the maximum price the bank will be willing to pay in any rounds $t < T$ solves the

[43]Note that this expression assumes that it is always optimal for the bank to purchase a unit in the current round if a price is actually quoted by some dealer, but this turns out to be optimal given that in equilibrium dealers quote only prices from $[\underline{p}_{t,u}, \overline{p}_{t,u}]$ and the definition of the upper bound $\overline{p}_{t,u}$.

indifference condition (with the definition $J(t,0)=0$):

$$\overline{p}_{T,u} = v \ \ \forall u > 0 \tag{37}$$

$$v - \overline{p}_{t,u} + \beta J(t+1, u-1) = \beta J(t+1,u) \ \forall u > 0 \text{ and } \forall t < T \tag{38}$$

One can show that the maximum prices have the following recursive structure (with the definition $\overline{p}_{t,0} = v$):

$$\overline{p}_{T,u} = v \ \ \forall u > 0 \tag{39}$$

$$v - \overline{p}_{T-1,u} = \beta \mathbb{E}\left[\sum_{j=1}^{u} \hat{s}^j_{T,u} - \sum_{j=1}^{u-1} \hat{s}^j_{T,u-1}\right] \tag{40}$$

$$v - \overline{p}_{t,u} = \beta \mathbb{E}\left[\hat{s}^1_{t+1,u} - \hat{s}^1_{t+1,u-1} + (1-\eta)^N (v - \overline{p}_{t+1,u}) + (1-(1-\eta)^N)(v - \overline{p}_{t+1,u-1})\right] \quad \forall t < T-1 \tag{41}$$

To fully characterize the equilibrium, it remains to compute $\mathbb{E}[\hat{s}^j_{t,u}]$ $\forall j = 1, \ldots, u$. Define

$$\hat{H}^j_{t,u}(v-p) := Prob(\hat{s}^j_{t,u} \leq v - p) = \sum_{k=0}^{j-1} C^k_N (\eta H_{t,u}(p))^k (1 - \eta H_{t,u}(p))^{N-k} \tag{42}$$

Note that[44] $\hat{H}^j_{t,u}(v - \underline{p}) = 1$ and $\hat{H}^j_{t,u}(v - \overline{p}) = \sum_{k=0}^{j-1} C^k_N \eta^k (1-\eta)^{N-k}$. We can then compute the expected surplus of the j^{th} unit purchased in round t as:

$$\mathbb{E}[\hat{s}^j_{t,u}] = -\int_{\underline{p}}^{\overline{p}} (v-p) d\hat{H}^j_{t,u}(v-p) \tag{43}$$

$$= -[(v-p)\hat{H}^j_{t,u}(v-p)]^{\overline{p}}_{\underline{p}} - \int_{\underline{p}}^{\overline{p}} \hat{H}^j_{t,u}(v-p)\, dp \tag{44}$$

$$\tag{45}$$

We have now fully characterized the equilibrium and can illustrate some of its properties. We solve the model numerically and show in figure 9 below some of the characteristics of the equilibrium price dynamics depending on some of the model parameters. The different panels show how the support of the quoted prices change through the trading rounds $[\underline{p}_t, \overline{p}_t]$ for different values of η, i.e.,

[44] Since $H_{t,u}(\underline{p}) = 0$ and $H_{t,u}(\overline{p}) = 1$.

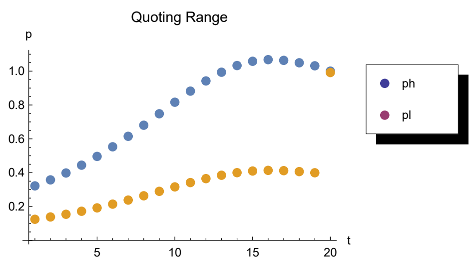
the ex-ante probability that a dealer quotes a price in a given round, and different assumptions about the realized trading, i.e., whether ex-post a dealer actually quoted a tradable price in a given round. Panels (a) and (b) have lower $\eta = 0.1$ compared to panels (c) and (d) with $\eta = 0.9$. And Panels (a) and (c) assume not a single trade occurs (that is no dealer quotes a price) prior to maturity. Instead panels (b) and (d) assume that one trade occurs (i.e., at least one dealer quotes a price) in period $t = 5$.

Comparing the panels we see that a very high $\eta = 0.9$, which implies that on average 9 dealers quote a price in every round, essentially leads to the competitive outcome, in that the pricing range is very narrow and close to zero (except for the last period where by definition $\overline{p}_T = 1$). Further, the dynamics of trading do not have a large impact on the trading price, that is panels (c) and (d) are very similar. Instead, if $\eta = 0.1$, which implies that few dealers expect to be quoting a price in any given round, then the price pattern is very different. Indeed, panel (a) and (b) show that in this case the price range increases significantly towards maturity. This pattern reflects the fact that early on dealers quote lower prices as they know they compete with future dealers. But that effect erodes as we approach maturity. Thus dealers' rents increase as we approach maturity. Further, comparing panel (a) and (b), we see that after a trade which reduces the target inventory of the bank, the pricing range drops, which shows that dealers' rents decrease with the target inventory. So market competitiveness increases with η and decreases with U the target inventory.

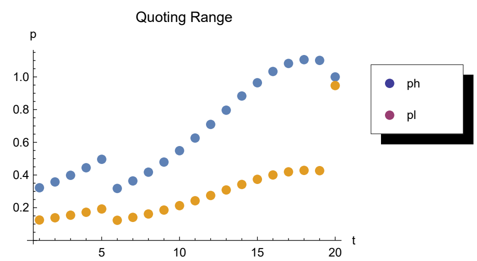
Surprisingly, we see that when the market is not very competitive (panels (a) and (b)), the maximum price ($\overline{p}_t$) at which the bank is willing to purchase a unit can exceed her reservation value of $v = 1$ as maturity approaches. While at first counter-intuitive, this phenomenon is best explained by considering a simpler two period example. Suppose that the bank wants to purchase 2 units in 2 periods from 2 dealers, who quote with probability 1 in every period. Suppose her reservation value is 1 per unit, so that if the bank enters period 2 and still needs to buy 2 units, then both dealers will quote a price of 1, since they are guaranteed to each sell their unit to the bank. Instead, if the bank enters period 2 and only needs to buy 1 unit, then Bertrand competition between the dealers will drive the price to 0. Thus the bank has an incentive in period 1 to pay up to $2 - \epsilon$ to buy one unit from the quoting dealer, so as to obtain the low price in the second period and thus reduce the total cost of purchasing the 2 units to $2 - \epsilon$. Depending on the parameters of the model, and on the realized inventory path, the bank may thus have an incentive to pay a price higher than its last period reservation value, to avoid giving too much market power to the dealers in the final rounds.

Figure 9. The four panels show the time pattern of the quoting range $[\underline{p}_t, \overline{p}_t]$ for different trading scenarios and different level of competition (η). Parameters are $T = 20$, $U_0 = 5$, $N = 10$, $v = 1$. The No-trade scenario assumes that not a single dealers quotes a price throughout $t \in [0, T = 20]$ (so units that remain to be purchased are $U_t = U_0 = 5 \; \forall t$). Instead, the Trade scenario assumes that one trade occurs in period 5 (so $U_t = U_0 - \mathbf{1}_{t \geq 5}$).

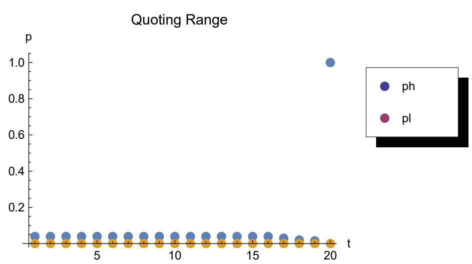
(a) Low $\eta = 0.1$, No Trade



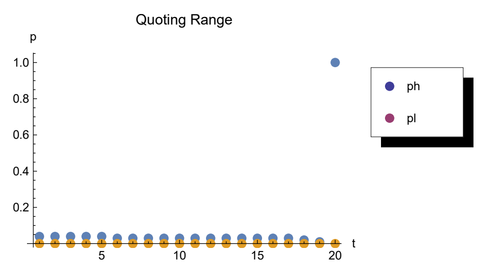
(b) Low $\eta = 0.1$, Trade



(c) High $\eta = 0.9$, No Trade



(d) High $\eta = 0.9$, Trade



5 Empirical analysis

The previous section showed that a model with imperfect competition is qualitatively able to generate the pattern of rapidly increasing prices towards maturity that we document is present during the PSPP around end-of-month. In this section, we test several additional qualitative predictions of our model to further establish the link between the price anomaly, the PSPP, and the degree of competition among bond dealers.

5.1 Is the price anomaly linked to the Eurosystem's purchases?

Our first prediction we test is whether bond prices increase over the month's end, across multiple trading rounds . To test this, we run a regression where we measure the impact of Eurosystem purchases on a specific bonds at day t within window j relative to the bonds that were not purchased:

$$\log(P_{i,j,t}/P_{i,j,-9}) = \gamma \times \text{D.Purchase}_{i,j,t} + \sum_{t=-9}^{T=8} \alpha_t \times \text{D}_t + \sum_{t=-9}^{T=8} \beta_t \times \text{D.Purchase}_{i,j,t} \times \text{D}_t + \epsilon_{i,j,t} \quad (46)$$

where $\text{D.Purchase}_{i,j,t}$ is a dummy variable that is equal to one when bond i is purchased at day t in window j and otherwise zero.[45] In the main specification, we control for bond-window fixed effects and standard errors are clustered at bond-window level. We also include the Bund tantrum window (April 15 - May 15, 2015).

The pattern of the β_t coefficients confirms and strengthens our previous results as shown Figure 10. We find a visible positive and substantial effect at the end-of-month: the bond holding return of purchased bonds increases more than the bond holding return of non-purchased bonds as we approach the end-of-month. Interestingly, the maximum of the bond holding return, relative to the beginning of the window, is reached two days before the end-of-month. This coincides with the last day in a given month on which Eurosystem trades count towards the monthly purchase targets since it takes two business days to settle the trade. In Figure A-III we provide the corresponding pattern when we estimate Equation 46 for yields.

[45]The comparison between purchased and not purchased bond yields results is similar to comparing eligible and ineligible bonds. Although all bonds in this study are German sovereign bonds, their eligibility is subject to fluctuations over time. For example, bonds were deemed ineligible once their yields dropped below the deposit facility rate. Even though our findings remain consistent when comparing eligible versus ineligible, interpreting these results can be complex. The act of purchasing could inadvertently make a security ineligible by driving the yield beneath the deposit facility rate. We have incorporated the results of this alternative specification into the appendix for reference and completeness.

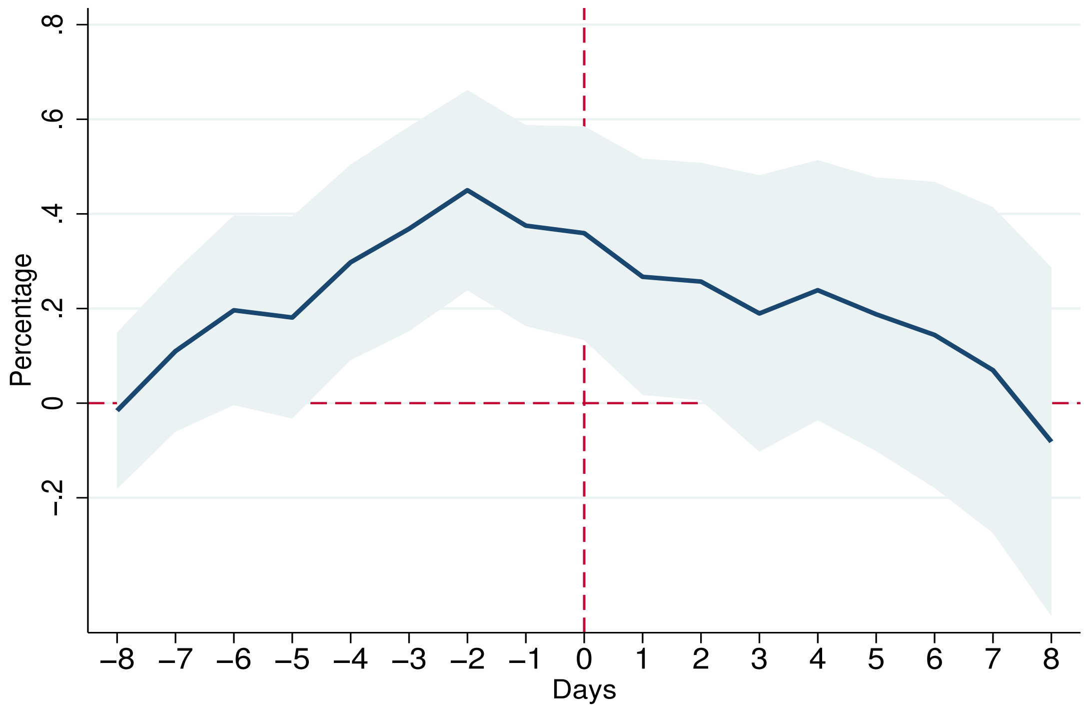


Figure 10. Eurosystem purchases and bond holding returns around end-of-month. This figure plots the interaction coefficients, β_t from a regression analysis. The dependent variable in this regression is the bond holding return $\log(P_{i,j,t}/P_{i,j,-9})$, where $P_{i,j,t}$ is the price of bond i on day t within window j (ranging from -9 to 8) and $P_{i,j,-9}$ indicates the price of the same bond on the end-of-window day ($t = -9$). The main independent variable is the interaction of the dummy variable, $\text{D.Purchase}_{i,j,t}$, that is equal to one when bond i is purchased on day t within window j and zero otherwise. The shadowed region depicts 99% confidence intervals.

Column (2) of Table 3 reports the coefficients plotted in Figure 10.[46] Then we proceed re-evaluate Equation (46), this time applying different set of fixed effects. In Column (1), we control for bond and window fixed effects. In Column (3) we control for window and window-maturity bucket fixed effects, while Column (4) we control for bond, window and window-maturity bucket fixed effects.[47] The use of interacted fixed effects enables a comparison between closely related bonds that differ solely on the basis of whether they have been purchased or not. Our analysis reveals that the coefficients across all variations remain consistent with those in Column (2).

In Columns (5) – (8) we replicate the previous exercise, this time excluding the quarter-end windows. The estimates around the end-of-month are smaller yet statistically significant and the bond holding return's maximum relative to the beginning of the window is still reached two days

[46]Table A-V reports the results for the yields.
[47]The maturity buckets use are identical to those outlined in Section 3.

before the end-of-month. Overall our estimates are consistent with our previous findings outlined in Section 3, suggesting that the lower degree of competition among dealers around end-of-quarters reinforces our differential effect on bond purchases. In the context of the model we present below, this can be explained by a reduction in competition among dealers to provide an executable quote around quarter end.

Table 3. Eurosystem purchases and bond holding returns around end-of-month - This table provides the interaction coefficients from a regression analysis, where the dependent variable is the bond holding return, computed as the logarithmic ratio of bond price $P_{i,j,t}$ to $P_{i,j,-9}$. In this context, $P_{i,j,t}$ denotes the price of bond i on day t within window j (extending from -9 to 8), and $P_{i,j,-9}$ represents the price of the same bond on the window's final day (i.e., $t = -9$). The primary independent variable is the interaction of a dummy variable, D.Purchase$_{i,j,t}$, and daily indicator variables. D.Purchase$_{i,j,t}$ takes the value of one when bond i is purchased on day t within window j, and is otherwise zero. Standard errors, clustered at the bond-window level, are indicated within parentheses. Significance levels are denoted as follows: $***$ for 1%, $**$ for 5%, and $*$ for 10%.

	(1) Base	(2) Base	(3) Base	(4) Base	(5) Without quarter-end	(6) Without quarter-end	(7) Without quarter-end	(8) Without quarter-end
-8	-0.004	-0.016	-0.009	-0.009	-0.063	-0.084	-0.079	-0.079
-7	0.083*	0.110*	0.108*	0.108*	0.070	0.048	0.032	0.033
-6	0.130**	0.196**	0.169**	0.168**	0.070	0.131*	0.112	0.109
-5	0.106	0.181**	0.152*	0.147*	0.046	0.116	0.081	0.076
-4	0.195***	0.298***	0.256***	0.255***	0.053	0.159*	0.115	0.109
-3	0.270***	0.368***	0.334***	0.328***	0.142*	0.265***	0.228***	0.220**
-2	0.399***	0.450***	0.405***	0.400***	0.253***	0.321***	0.278***	0.271***
-1	0.335***	0.375***	0.347***	0.343***	0.123	0.211**	0.176**	0.170**
0	0.353***	0.359***	0.323***	0.320***	0.036	0.124	0.080	0.075
1	0.274***	0.267***	0.227**	0.222**	0.036	0.050	0.004	0.002
2	0.283***	0.257***	0.210**	0.206**	0.036	0.018	-0.026	-0.025
3	0.183*	0.190*	0.141	0.139	-0.125	-0.091	-0.138	-0.137
4	0.246**	0.239**	0.189*	0.184*	0.037	0.013	-0.029	-0.028
5	0.192*	0.188*	0.150	0.148	0.002	-0.043	-0.068	-0.067
6	0.181	0.144	0.118	0.120	-0.060	-0.062	-0.085	-0.082
7	0.142	0.070	0.044	0.047	-0.065	-0.116	-0.139	-0.138
8	0.022	-0.082	-0.087	-0.085	-0.123	-0.226	-0.233	-0.234
Obs.	19,274	19,271	19,274	19,274	14,720	14,717	14,720	14,720
R^2	0.2385	0.5781	0.5566	0.5583	0.2311	0.5452	0.5255	0.5270
Bond FE	Yes	Yes	-	Yes	Yes	Yes	-	Yes
Window FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Window X Bond FE	-	Yes	-	-	-	Yes	-	-
Window X Maturity FE	-	-	Yes	Yes	-	-	Yes	Yes

We now study the determinants of the purchase decision D.Purchase by the Eurosystem looking at the PSPP eligibility criteria that were instrumental in identifying the price anomaly. As we established in Section 2, we define a bond i as eligible for purchase on day t with an indicator variable $\text{Eligible}_{i,t}$ that is equal to 1 if i) the yield of bond i on day t is above the ECB deposit facility rate; and/or ii) the time-to-maturity is above two years or below thirty years; and/or iii) the bond i is not subject to the blackout period which affects newly issued or reissued bonds in an auction and bonds with similar residual time-to-maturity of the auctioned bond (Arrata et al. (2020), De Santis and Holm-Hadulla (2020)).

We start with a panel regression where the independent variable D. $\text{Purchase}_{i,t}$ is an indicator variable that is equal to 1 if bond i is purchased on day t and zero otherwise and the dependent variable is $\text{Eligible}_{i,t}$. Table 4 reports the results. Column (1) shows that, on average, the probability of a German sovereign bond being purchased by the Eurosystem due to the eligibility criteria. In Column (2), we control for bond and day fixed effects and the economical and statistical significance of the coefficient on $\text{Eligible}_{i,t}$ is slightly larger. In Column (3), we distinguish between the three main eligibility criteria: the deposit rate floor rule, time-to-maturity, and the blackout period. The latter combines two indicator variables that define the bond as ineligible when it is issued or reissued, or when is a close substitute of the auctioned bond. As expected, both $\text{Ineligible}_{i,t}$ variables have a statistically and economically significant negative coefficients on the purchase decision. The coefficient associated with the time-to-maturity eligibility is not statistically significant. However, this rule mainly overlaps with the deposit rate rule, as bonds that have a yield below the ECB deposit rate are predominantly short and medium-term bonds. Finally, we include the bid-ask spread and the special repo rate of bond i on day t as further factors that could influence the purchase decision (Column (4)). The coefficients of these additional measures are statistically insignificant. Overall, our results imply that the daily purchase decision is mainly affected by eligibility criteria that are unique to the Eurosystem as an investor compared to other large investors.

After the regression analysis, Figure 11 provides a box-whisker plot of the ratio of the amount of bonds purchased in a day over the total amount of bonds purchased in the same window. The figure draws a box ranging from the first to the third quartile, with a line indicating the median. The "whiskers" going from the box to the adjacent values represent the highest and lowest values that are not farther from the median than 1.5 times the interquartile range. If the Eurosystem consistently

Table 4. Bonds purchased by the Eurosystem and eligibility - This table presents the outcomes of a panel regression, wherein the independent variable, D. Purchase$_{i,t}$, is an indicator that equals 1 if bond i is purchased on day t and zero otherwise. The panel regression incorporates bond and day fixed effects in Columns (2) − (4). Standard errors, reported in parentheses, are two-way clustered at the date and bond levels for Columns (2) − (4). $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1)	(2)	(3)	(4)
Eligible$_{i,t}$	0.527***	0.548***		
Eligible$_{i,t}$ - deposit rate rule			0.553***	0.559***
Eligible$_{i,t}$ - time-to-maturity			0.050	0.048
Ineligible$_{i,t}$ - black-period			-0.486***	-0.504***
Bid-ask spread$_{i,t}$				0.168
Special repo rate$_{i,t}$				-0.030
Obs.	19,274	19,274	19,274	18,872
R^2	0.3230	0.3966	0.3943	0.3970
Bond FE	No	Yes	Yes	Yes
Day FE	No	Yes	Yes	Yes

purchases the same amount of bonds every day, the ratio should be 5%(= 1/20 days). We observe that the median is 4.79% and therefore it lies slightly below this target. The figure shows that the distribution across the days is pretty stable indicating that the Eurosystem maintains a continuous market presence throughout the window with the exception of the end-of-month. Interestingly, trading activity clearly drops in days −3 and −2 in some windows. This suggests that the decline in Eurosystem trading activity may be linked to the run-up in bond prices quoted by the dealers.

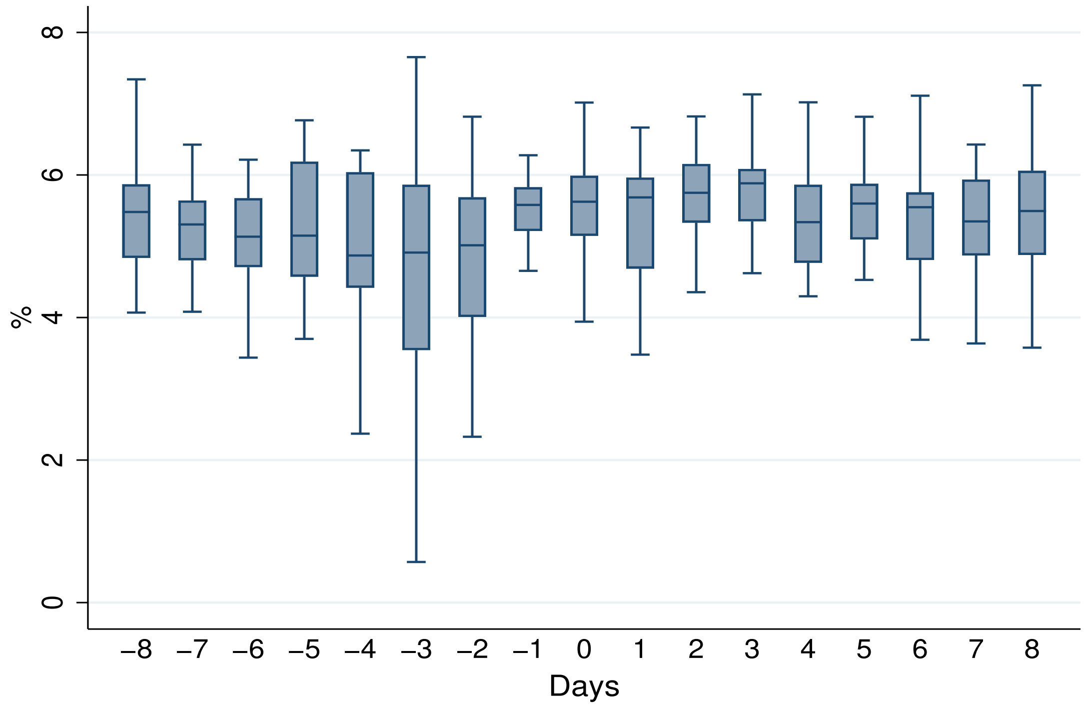


Figure 11. Eurosystem trading activity within window. This figure provides a box-whisker plot of the ratio of the amount of bonds purchased on a specific day t over the total amount of bonds purchased in the same window. The figure draws a box raging from the first to the third quartile with a line at the median. The "whiskers" going from the box to the adjacent values are the highest and lowest values that are not farther from the median than 1.5 times the interquartile range. t ranges from -8 to 8 (including $t = 0$) and $t = 0$ being the last day of the month.

5.2 Is the price anomaly amplified when the Eurosystem buys more bonds?

In this subsection, we test two key model implications of our model. First, we investigate whether the degree of competition among dealers is linked to the price anomaly. The model predicts that the lower the competition, the higher the price increase over the trading rounds as we approach the end-of-month. This hypothesis is consistent with our earlier observations of a more pronounced price pattern at quarter-end, which aligns with our simple model of imperfect competition where the central bank is bargaining with a few large dealers over a finite number of rounds. To further test this prediction, we first count the number of counterparties the Eurosystem traded with during the last five trading days of the month within each window. Focusing on the median of this measure, we identify seven windows with a lower number of counterparties. Two of them coincide with the quarter-end windows. We then estimate our main specification (46) on windows with a lower number of counterparties. Table (5) reports the results of this regression in Column (2) together with the full sample results from our base specification in Column (1) for comparison (see also Column (2) of Table 3).

Table 5. Competition and Frontloading: Eurosystem purchases and bond holding returns around end-of-month - This table presents the interaction coefficients derived from a regression analysis where the dependent variable is the bond holding return, computed as the logarithmic ratio of the bond price $P_{i,j,t}$ to $P_{i,j,-9}$. Here, $P_{i,j,t}$ signifies the price of bond i on day t within window j (ranging from -9 to 8), and $P_{i,j,-9}$ represents the price of the same bond on the final day of the window ($t = -9$). The primary independent variable is the interaction of a dummy variable, D.Purchase$_{i,j,t}$, and daily indicator variables. D.Purchase$_{i,j,t}$ assumes a value of one when bond i is purchased on day t within window j, and zero otherwise. Standard errors, clustered at the bond-window level, are enclosed in parentheses. $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1) Base	(2) Low counterparties	(3) Front loading
-8	-0.016	-0.126	0.022
-7	0.110*	0.196	0.150**
-6	0.196**	0.290*	0.237*
-5	0.181**	0.287*	0.238**
-4	0.298***	0.524***	0.210**
-3	0.368***	0.590***	0.602***
-2	0.450***	0.631***	0.399***
-1	0.375***	0.561***	0.407***
0	0.359***	0.541***	0.263**
1	0.267***	0.146	-0.035
2	0.257***	0.338	0.162
3	0.190*	0.128	0.054
4	0.239**	0.034	0.133
5	0.188*	-0.089	0.184
6	0.144	-0.208	-0.158
7	0.070	-0.211	-0.149
8	-0.082	-0.303	-0.301
Obs.	19,271	6,389	3,657
R^2	0.5781	0.5983	0.3496
Bond FE	Yes	Yes	Yes
Window FE	Yes	Yes	Yes
Window X Bond FE	Yes	Yes	Yes

The pattern of the β_t is consistent with our model prediction: the lower the number of counterparties the Eurosystem trades with, the larger the pattern of the bond holding return of purchased bonds relative to non-purchased bonds as we approach the end-of-month.[48]

Second, we now test the model's prediction that bond prices should increase more when the central bank has to buy a larger number of bonds. To test this prediction we look at windows where Eurosystem increased purchases, explicitly deviating from the monthly fixed target.

To motivate this analysis, we use this statement by Benoît Coeure, ECB board member, on 18 May 2015: *"Against this background, we are also aware of seasonal patterns in fixed-income market activity with the traditional holiday period from mid-July to August characterised by notably lower market liquidity. The Eurosystem is taking this into account in the implementation of its expanded asset purchase programme by moderately* **frontloading** *its purchase activity in May and June, which will allow us to maintain our monthly average of 60 billion, while having to buy less in the holiday period."*.[49]

Thus, the Eurosystem increased the amount of purchases before the summer and before the end-of-year. We re-estimate our main specification (46) on the *"frontloading"* windows (see Column (3) of Table (5). In instances of consecutive front-loading windows, our focus is on the first window. The intensity of purchases in these windows does not necessarily persist into subsequent ones, as there is no predetermined purchase target. The monthly target is typically met within the first window, leaving traders uncertain about the necessity for additional purchases in the second window. Moreover, the liquidity in the market begins to diminish from the second window onward. Note that this situation has occurred twice within our sample and coincided with the end of a quarter on both occasions.

Our estimates show a more pronounced asymmetric pattern of the β_t around the end-of-month in the frontloading windows, compared to the full specification. Our results suggest that the Eurosystem, on average, paid a higher price at the end-of-month when they increasedincreased purchases due to front-loading implementation. Interestingly, the maximum of the differential β_t is reached earlier than the usual two days before of the end-of-month when Eurosystem trades count towards the monthly purchase targets. This empirical findings is consistent with model prediction when the market is not very competitive and the central bank has to buy large amount of bonds the

[48]Table (A-VI) reports consistent results for the yields.

[49]See `https://www.ecb.europa.eu/press/key/date/2015/html/sp150519.en.htm`.

maximum price at which the central bank is willing to purchase bonds can exceed her reservation value as maturity approaches. In fact the central bank may have an incentive to pay a price higher than its last period reservation value, to avoid giving too much market power to the dealers in the final rounds.

Finally, we note that the more pronounced asymmetric pattern in the front-loading windows emphasizes that the price anomaly we document is not linked to bond market liquidity conditions. Figure 12 shows the evolution of the Tradeweb German sovereign bond market liquidity indicators for the two maturity buckets targeted by the Eurosystem: $5.5 - 11.5$ and > 11.5 years.[50] The $5.5 - 11.5$ years bucket indicator, based on German central sovereign bonds that have a time-to-maturity between 5.5 and 11.5 years, is as the liquidity benchmark in the euro area. An increase in the liquidity indicator points to a deterioration of bond market liquidity conditions. The figure shows a clear pattern in German bond market liquidity as pointed out by Benoît Coeure and highlighted by the shaded areas. There is a decline in market liquidity from beginning of July to end of August 2015 and 2016 and from mid-December to mid-January 2015 and 2016. Indeed, this decline in bond trading liquidity was the reason for the ECB's 'front-loading' decision.

[50]The sovereign Tradeweb liquidity indicators are country-specific within the euro area. They are based on executed prices and volume data from the Tradeweb platform comparing the executed price to the mid price at security level. The distance from the mid price is used as a measure of bond market liquidity: values further away from the mid price are seen as less liquid. Each index is derived from the duration-weighted yield (in basis points) difference from Tradeweb composite mid prices across all trades. The German $5.5 - 11.5$ years bucket is selected as the liquidity benchmark. This bucket is defined as 1 at the start of the index on 2 January 2008. On the same date a multiplier is calculated for all other bucket indices to reflect their relative liquidity level.

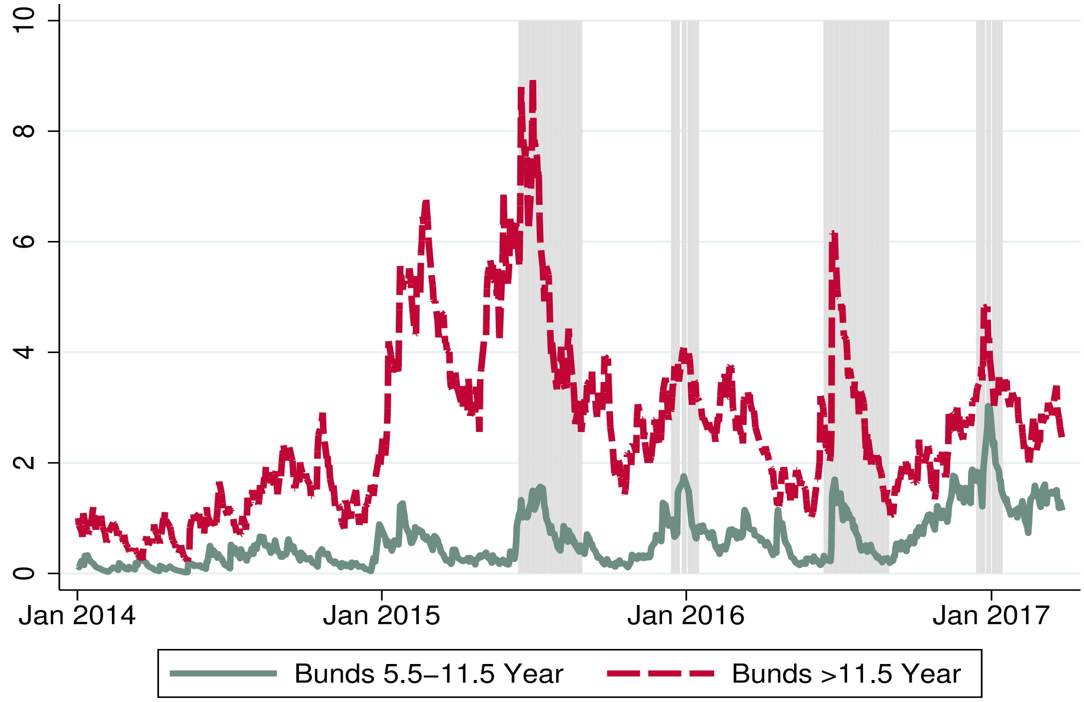


Figure 12. Tradeweb sovereign bond market liquidity indicators for German sovereign bonds (maturity bucket $5.5 - 11.5$ year and > 11.5 year).

5.3 Impact of end-of-month surge in bond prices

To assess the economic impact of bond prices increasing at the end of the month for the Eurosystem, we perform the following calculation. First, we compute the real portfolio as the overall amount of purchases from day -9 to day 0 for each window, defined as

$$\sum_{t=-9}^{T=0} \sum_{i=1}^{U_t} w_{i,t} \times p_{i,t}$$

where $w_{i,t}$ is amount purchased of bond i at day t by the Eurosystem at day t, $p_{i,t}$ is the Bloomberg price and U_t is number of bonds purchased at day t.

Second, we compute the beginning-of-period portfolio as the total nominal amount of purchases from day -9 to day 0 times the bond prices we observe at day -9 as[51]

$$\sum_{t=-9}^{T=0}\sum_{i=1}^{U_t} w_{i,t} \times p_{i,-9}.$$

The difference between these two portfolios

$$\Delta P = \sum_{t=-9}^{T=0}\sum_{i=1}^{U_t} w_{i,t} \times p_{i,t} - \sum_{t=-9}^{T=0}\sum_{i=1}^{U_t} w_{i,t} \times p_{i,-9} \tag{47}$$

offers an estimate of the impact of bond prices changing at the end of the month changeson the Eurosystem. This measure is inspired by the implementation shortfall approach (Perold (1988)). This computation is a standard metric in market microstructure to measure the extent to which markets are illiquid. Measuring an expected measure shortfall does not imply a market loss for the Eurosystem and does not necessarily mean that the Eurosystem could purchase the entire desired amount at the initial price.[52] Moreover, our measure (47) is close to the cost measure implemented by Lou, Yan, and Zhang (2013) who quantify the amount of money the US Treasury could have saved were it able to issue US Treasury securities at the average secondary market price during few days before and following each auction.

Figure 13 plots ΔP for each window (expressed as a percentage of the real portfolio) for German sovereign bonds. The figure also plots the differential yield between the average yield of German bonds at day -9 and the average yield of those same bonds at day 0 for each window. A positive differential yield points to a yield (price) decrease (increase). We expect a negative impact for Eurosystem when the yield differential is positive. Overall, we observe a positive ΔP indicating that the price anomaly we document occurs in most of the windows. Interestingly, we also observe a certain variation in our measure over time. In two months we observe a large and negative implied cost ΔP implying that bond prices decreased at the end of the month. The first episode is the "Bund Tantrum" occurred at the end of April 2015 and previously discussed in Section 2. The second one occurs in the second half of April 2016. On 1 April 2015, the ECB's monthly asset

[51]An alternative approach would be to compute the measure using the executed prices by Eurosystem instead of the Bloomberg quotes. However, the executed prices at time -9 are not available for all the securities purchased over the 10$-$day period to compute the second leg because Eurosystem does not buy all the securities on each day t.

[52]As markets are not perfectly, infinitely liquid and deep, the average price at which an investor transacts a desired quantity may deviate from the initial price at which she starts to transact.

purchases rose by 20 billion euros to a total of 80 billion euros, with a significant proportion of that additional buying targeted at government bonds, thereby exerting upward pressure on prices at the beginning of the same month.

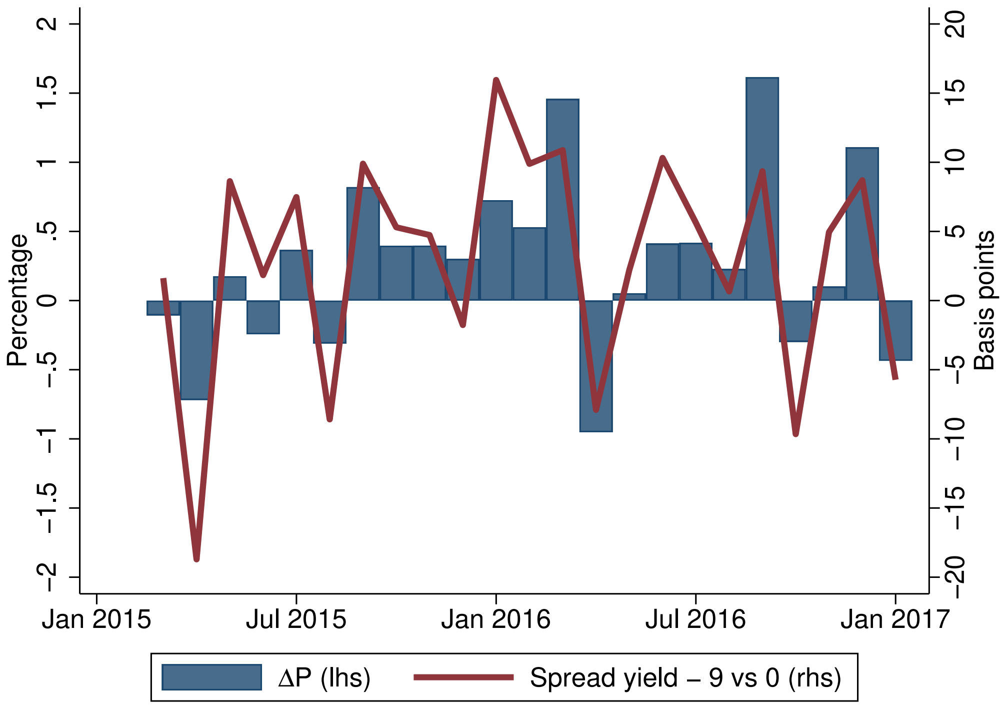


Figure 13. The figure plots the difference between the real portfolio, as the overall amount of purchases from day −9 to day 0 for each window, and the beginning-of-period portfolio, calculated as the total nominal amount of purchases from day −9 to day 0 times the bond prices we observe at day −9, as percentage of the real portfolio (left-hand side). The figure also plots the differential yield between the average yield of German bonds at day −9 and the average yield of the same bonds at day 0 for each window (right-hand side).

Panel A of Table (6) shows the statistics of our monthly implied costs of bond prices increasing at the end of the month using our ΔP measure for the entire sample. We compute our measure also using the average prices between day −9 and day −7 (Price [-9,-7]) to compute the beginning-of-period portfolio. We compute the implied cost borne by the Eurosystem both in euro terms and as a fraction of the overall amount of purchases from day −9 to day 0 for each window. Finally, we also re-compute our measure using Trax prices , which are daily executed prices.

Based on our estimates, the impact due to the difference in prices of German sovereign bonds is on average euro 14.7 million per month of the market value of the securities purchased in the last 10

Table 6. Monthly implied costs of bond prices increasing at the end of the month - This table reports the average, standard deviation, minimum and maximum of ΔP which is the difference between the real portfolio as the overall amount of purchases from day -9 to day 0 for each window and the beginning-of-period portfolio as the total nominal amount of purchases from day -9 to day 0 times the bond prices we observe at day -9 (Price -9) and alternatively times the average price between day -9 and day -7 (Price [-9,-7]) for each window. We compute the measure using Bloomberg BGN and Trax prices. Panel A reports the results for the entire sample from March 15, 2015 to February 15, 2017. Panel B reports the results for the quarter-end windows.

		Mean	St.dev	Min	Max
Panel A - Full sample					
Bloomberg BGN					
Price -9	Euro mill.	14.75	44.83	-80.93	150.02
Price [-9,-7]	Euro mill.	8.76	36.48	-75.94	115.65
Price -9	%	0.26	0.63	-0.95	1.62
Price [-9,-7]	%	0.16	0.49	-0.89	1.25
Trax					
Price -9	Euro mill.	13.53	43.49	-89.98	145.65
Price [-9,-7]	Euro mill.	9.46	34.05	-73.92	107.88
Price -9	%	0.25	0.61	-1.06	1.66
Price [-9,-7]	%	0.17	0.47	-0.87	1.23
Panel B - Quarter-end					
Bloomberg BGN					
Price -9	Euro mill.	41.66	54.73	-12.84	150.02
Price [-9,-7]	Euro mill.	26.04	42.85	-18.44	115.65
Price -9	%	0.67	0.69	-0.24	1.62
Price [-9,-7]	%	0.39	0.51	-0.35	1.25
Trax					
Price -9	Euro mill.	40.05	50.65	-12.09	145.65
Price [-9,-7]	Euro mill.	26	39.96	-17.97	107.88
Price -9	%	0.66	0.64	-0.23	1.66
Price [-9,-7]	%	0.40	0.49	-0.34	1.23

days of each month. As expected, the implied cost decreases when we use an average price due to the bond prices increasing at the end of the month pattern we document in Section 3. The average cost substantially increases in quarter-end month from euro 14.7 million to euro 41.66 million when dealers' activity in the bond market falls as the cost of expanding their balance sheet increases due to regulation (see Panel B of Table (6)). Our estimates are slightly lower when we use Trax prices instead of Bloomberg BGN prices.

The total yearly impact amounts to euro 169 million during our sample period. This amount decreases to euro 100 million when we use the average price between day -9 and day -7 to compute the beginning-of-period portfolio. Of course, we do not claim that the estimated cost could have been entirely saved through a different design of asset purchase program and/or through a different trading mechanism. However, acknowledging this cost is an essential first step to assess and improve the design of asset purchase programs and the efficiency of the trading mechanism used by the central bank. Moreover, our estimates suggest the implied costs are substantial in particular at the quarter-end due to bank regulation that can negatively affect competition among dealers.

6 Conclusions

Throughout the implementation period of the ECB's PSPP, the prices (yields) of German sovereign bonds targeted by the PSPP increase (decrease) predictably towards month-end and drop (increase) subsequently from March 2015 to February 2017. This pattern is more pronounced, (i), on days and for bonds which are being purchased by the central bank at the time, (ii) in 'front-loading' months when the central bank purchases more (outside the summer and December periods which are typically less liquid), (iii), in months when the central bank trades with fewer counterparties, and, (iv), at quarter-ends, when more constrained banks are less likely to act as intermediaries.

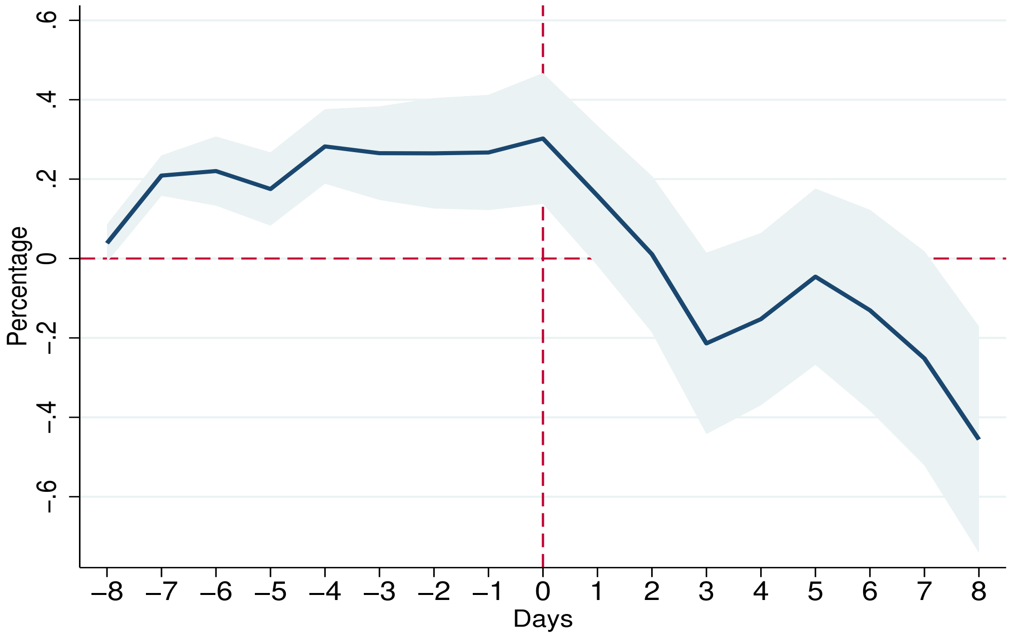
Our empirical results are consistent with a simple sequential search-bargaining model where the central bank buys several units over several trading rounds. With imperfect competition among dealers, dealers' bargaining power and their expected rents increase as end-of-month approaches.

Our findings have potential implications for the design of asset purchase programs. First, thet results suggest that the Eurosystem should consider moving away from committing to fixed euro notional purchases at fixed dates originally introduced to strengthen the perception that the ECB was resolute in executing the PSPP (Rostagno et al. (2021)). The implicit monthly purchase target for a large country as Germany can increase the price pressure effect by giving more bargaining power to dealers towards each end-of-month. One way to ease such a constraint could be to have no purchase target at all or to define the amount as a total envelope over a longer period similarly to the ECB's PEPP.

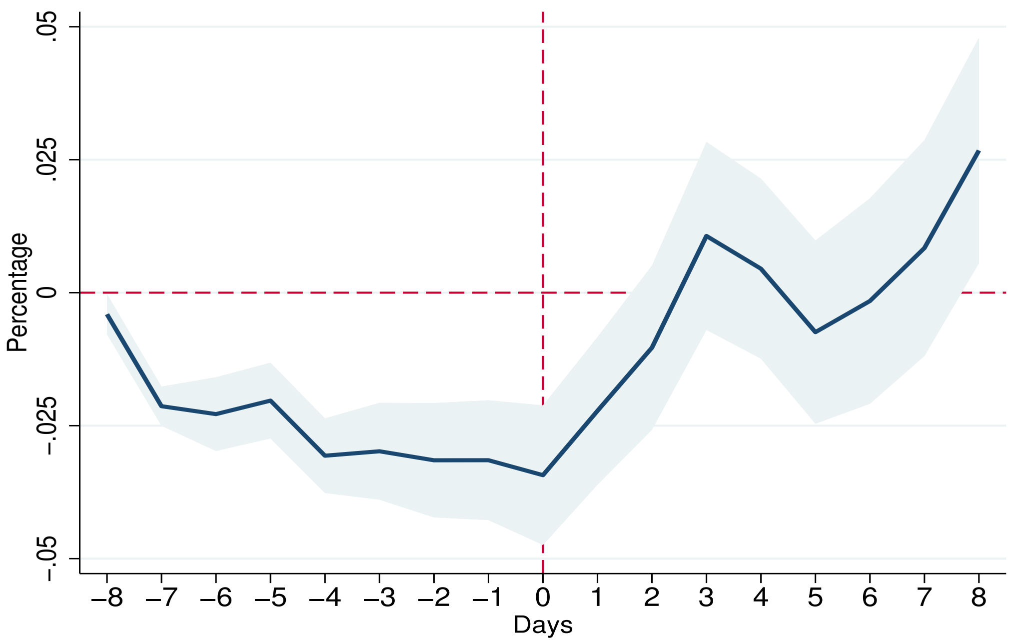
Second, the Eurosystem should consider moving towards trading on broader platforms that are open to a larger number of counterparties. This would stimulate competition from other potential sellers. Although several Eurosystem national central banks have used reverse auctions to target specific securities under the PSPP (Hammermann et al. (2019)), it is feasible to envision the establishment of regular auctions possibly via a centralized electronic trading platform at the Eurosystem level. This platform could accommodate all dealers, including those beyond the central bank's counterparties, allowing them to list the quantities they have available for the Eurosystem's purchase. The platform could potentially be opened up to non-banks, such as large insurance companies or mutual funds, who might also be willing to trade their fixed-income securities inventory. During times of market stress, a more "open" trading platform might be useful as the central bank can act as a "buyer of last resort" (Duffie (2020)). It would also help alleviate less competitive pricing by dealers that are constrained in their intermediation capacity at specific points in time, such as around quarter-ends and year-ends due to regulatory requirements (Breckenfelder and Ivashina (2021)). However, a detailed cost-benefit analysis would be necessary to assess the feasibility of such measures.

Finally, the Eurosystem modified the PSPP eligibility criteria to face the shortage of German sovereign bond securities. Expanding the set of securities eligible for PSPP purchases at the end of 2016 increased the availability of targetable securities potentially limiting the bargaining power of dealers at the end of the month. We leave the analysis of such changes to the PSPP to future research.

A-I Appendix

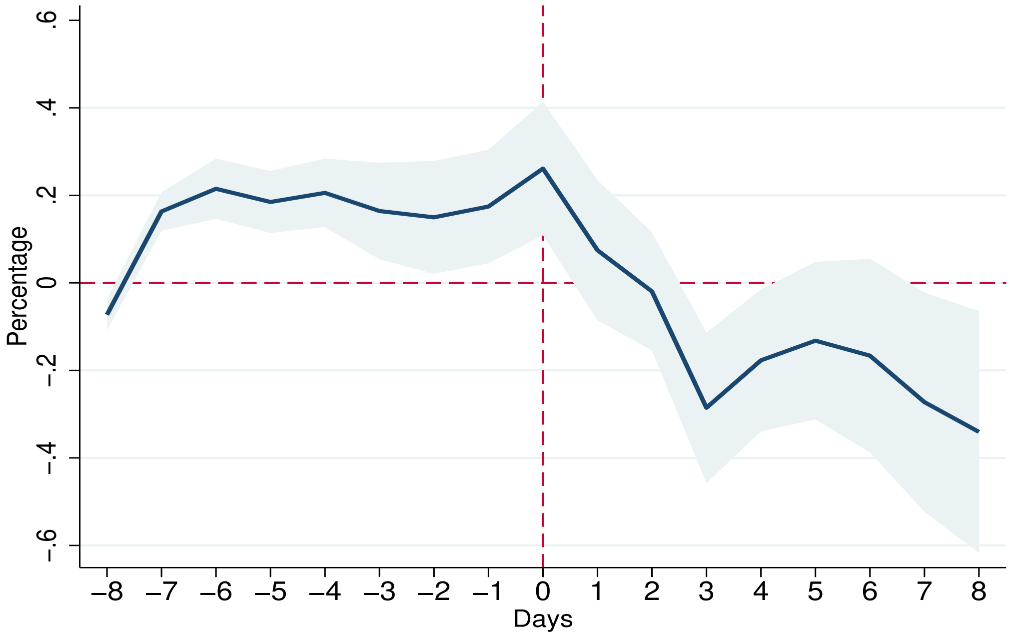


(a) Holding returns

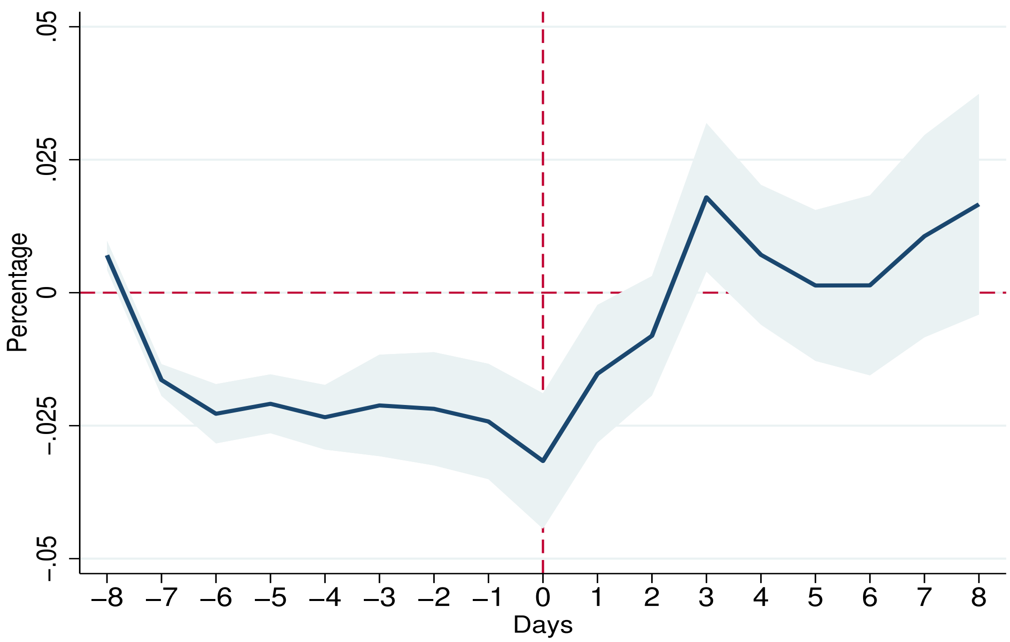


(b) Yield changes

Figure A-I. Holding returns and yields of PSPP eligible bonds around end-of-month - all windows. The figure plots the coefficients α_t from the OLS regression. In panel (a) the dependent variable is $\log(P_t/P_{-9})$, where P_t is the price of the bond at day t. In panel (b) the dependent variable is $Y_t - Y_{-9}$, where Y_t is the yield on day t. The bond yields and prices are from BGN Bloomberg. t ranges from -9 to 8 (including $t = 0$) and $t = 0$ is the last day of the month. The main independent variable is daily indicator variables. Shadow area is 99%-confidence interval.



(a) Holding returns



(b) Yield changes

Figure A-II. Holding returns and yields of PSPP eligible bonds around end-of-month - without quarter ends. The figure plots the coefficients α_t from the OLS regression. In panel (a) the dependent variable is $\log(P_t/P_{-9})$, where P_t is the price of the bond at day t. In panel (b) the dependent variable is $Y_t - Y_{-9}$, where Y_t is the yield on day t. The bond yields and prices are from BGN Bloomberg. t ranges from -9 to 8 (including $t = 0$) and $t = 0$ is the last day of the month. The main independent variable is daily indicator variables. Shadow area is 99%-confidence interval.

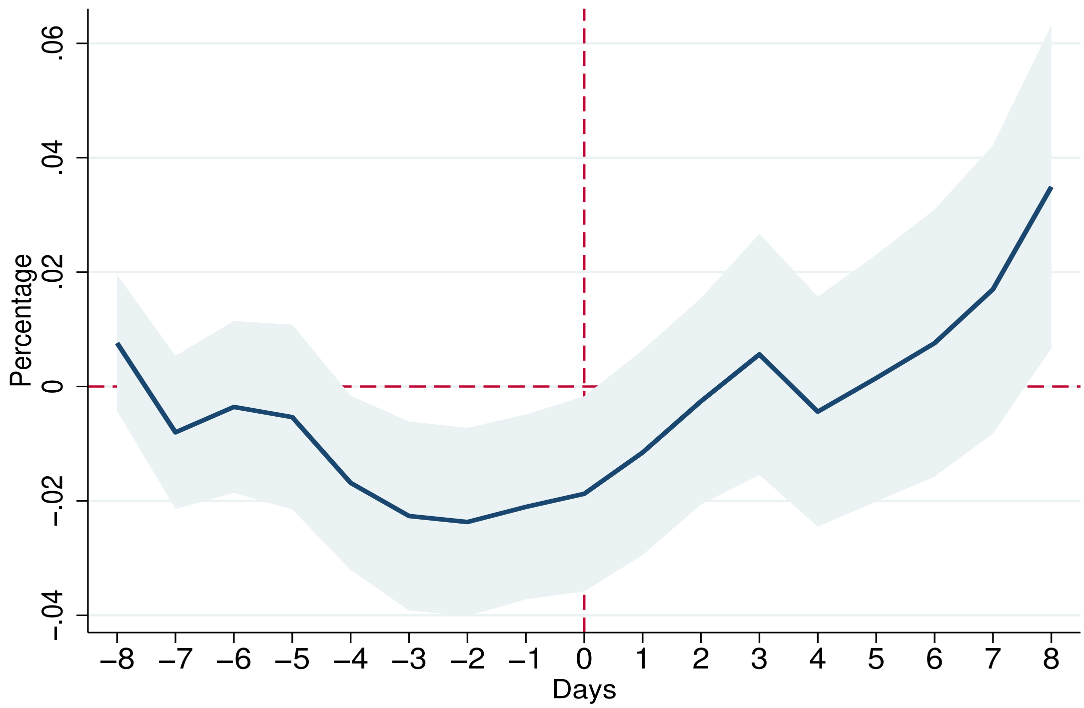


Figure A-III. Eurosystem purchases and bond yields around end-of-month. The figure plots the interaction coefficients β_t from an OLS regression. The dependent variable is $Y_{i,j,t} - Y_{i,j,-9}$, where $Y_{i,j,t}$ is the yield of the bond i at day t of window j (from -9 to 8) and $Y_{i,j,-9}$ is the yield of the same bond on the end-of-window day ($t = -9$). The main independent variable is the interaction of the dummy variable D.Purchase$_{i,j,t}$, that is equal to one when bond i is purchased at day t in window j and otherwise zero, and daily indicator variables. Shadow area is confidence intervals at 99%.

Table A-I. Summary statistics - Regression sample

	Obs.	Mean	St.dev
Panel A - Outstanding universe			
Time-to-maturity (years)	19,656	7.80	7.66
Coupon rate (%)	19,656	2.65	1.85
Price	9,656	120.73	24.66
Yield	19,655	-0.02	0.55
Outstanding amount (euro mill.)	19,656	17,164	4,787
Special repo rate (%)	19,211	-0.44	0.23
Panel B - PSPP eligibility			
Dum. eligible	19,656	0.53	0.50
Dum. eligible - deposit rate	19,656	0.56	0.50
Dum. eligible - time-to-maturity	19,656	0.77	0.42
Dum. ineligible - auction	19,656	0.01	0.12
Panel C - PSPP purchases			
Dum. purchase	19,656	0.31	0.46
Time-to-maturity (years)	6,004	11.74	7.55
Coupon rate (%)	6,004	3.01	1.84
Price	6,004	132.37	27.66
Yield	6,004	0.28	0.51
Outstanding amount (euro mill.)	6,004	17,767	3,899
Special repo rate (%)	5,998	-0.44	0.25
Monthly cum. purchases / Outstanding (%)	699	1.41	1.12
Monthly cum. purchases / Trax volume (%)	621	10.73	11.06
Purchased amount	6,004	28.41	21.48
Num. counterparties	6,004	1.21	0.57

Table A-II. Bond yield changes around the end-of-month - This table presents the coefficients from a regression analysis where the dependent variable is the change in bond yield, represented as $Y_{i,j,t} - Y_{i,j,-9}$. Here, $Y_{i,j,t}$ signifies the yield of bond i on day t within window j (from -9 to 8), and $Y_{i,j,-9}$ corresponds to the yield of the same bond on the last day of the window ($t = -9$). The independent variable is the day t, varying from -9 to 8 (including $t = 0$), where $t = 0$ represents the end-of-month day. The regression incorporates bond-window fixed effects, and standard errors are clustered at the bond-window level. Standard errors are indicated in parentheses. $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
	PSPP eligible					PSPP ineligible
	Base	Without quarter-end	Without newly issued bonds	Without benchmark bonds	With Bund tantrum	
-8	-0.004**	0.007***	-0.004***	-0.004***	-0.006***	-0.002*
-7	-0.023***	-0.016***	-0.023***	-0.023***	-0.022***	-0.003**
-6	-0.028***	-0.023***	-0.028***	-0.028***	-0.024***	-0.014***
-5	-0.027***	-0.022***	-0.027***	-0.026***	-0.023***	-0.009***
-4	-0.037***	-0.025***	-0.037***	-0.037***	-0.033***	-0.012***
-3	-0.037***	-0.023***	-0.037***	-0.037***	-0.032***	-0.015***
-2	-0.039***	-0.024***	-0.039***	-0.040***	-0.034***	-0.020***
-1	-0.046***	-0.026***	-0.046***	-0.047***	-0.034***	-0.020***
0	-0.054***	-0.035***	-0.055***	-0.055***	-0.038***	-0.025***
1	-0.042***	-0.018***	-0.042***	-0.042***	-0.026***	-0.021***
2	-0.036***	-0.010**	-0.036***	-0.036***	-0.014**	-0.025***
3	-0.018***	0.015***	-0.018***	-0.018***	0.007	-0.024***
4	-0.025***	0.005	-0.025***	-0.024***	0.001	-0.029***
5	-0.035***	-0.000	-0.035***	-0.035***	-0.011*	-0.033***
6	-0.033***	-0.000	-0.032***	-0.032***	-0.005	-0.041***
7	-0.023***	0.008	-0.023***	-0.022***	0.005	-0.042***
8	-0.005	0.013	-0.005	-0.004	0.024***	-0.034***
Obs.	9,769	7,244	9,520	9,518	10,431	8,933
R^2	0.5474	0.4758	0.5477	0.5459	0.5971	0.6427

Table A-III. Bond holding returns around the end-of-month and maturity buckets (in years) - This table presents the coefficients from a regression analysis, where the dependent variable represents the bond holding return, defined as $\log(P_{i,j,t}/P_{i,j,-9})$. Here, $P_{i,j,t}$ refers to the price of bond i on day t within window j (ranging from -9 to 8), and $P_{i,j,-9}$ indicates the price of the same bond on the last day of the window ($t = -9$). The independent variable is the day t, spanning from -9 to 8 (including $t = 0$), with $t = 0$ marking the end of the month. The regression incorporates bond-window fixed effects, and standard errors are clustered at the bond-window level. Standard errors are detailed in parentheses. $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1) $0 < 2$	(2) $2 - 5$	(3) $5 - 10$	(4) $10 - 20$	(5) > 20
-8	-0.012***	-0.003	0.025*	0.046	0.160*
-7	-0.021***	0.006	0.104***	0.207***	0.528***
-6	-0.027***	0.032***	0.148***	0.287***	0.671***
- 5	-0.036***	0.017**	0.118***	0.197**	0.507***
-4	-0.043***	0.021**	0.172***	0.317***	0.851***
- 3	-0.052***	0.021*	0.171***	0.306***	0.845***
- 2	-0.059***	0.032**	0.209***	0.324***	0.850***
- 1	-0.073***	0.019	0.232***	0.407***	1.034***
0	-0.080***	0.030**	0.294***	0.514***	1.225***
1	-0.091***	0.010	0.198***	0.289**	0.776***
2	-0.098***	0.013	0.171***	0.215*	0.567**
3	-0.110***	-0.017	0.069	0.018	0.201
4	-0.122***	-0.014	0.122***	0.119	0.388
5	-0.130***	-0.006	0.192***	0.242*	0.563**
6	-0.133***	0.005	0.196***	0.230	0.472
7	-0.143***	-0.006	0.135***	0.092	0.179
8	-0.160***	-0.051***	0.011	-0.149	-0.297
Obs.	4,044	4,941	5,340	2,235	2,142
R^2	0.7679	0.6061	0.5423	0.5324	0.5304

Table A-IV. Robustness - Bond holding returns of PSPP eligible bonds around the end-of-month - This table reports the coefficients of the regression where the dependent variable is the bond holding return $\log(P_{i,j,t}/P_{i,j,-9})$ - Columns (1) - (3). $P_{i,j,t}$ is the price (yield) of the bond i at day t of window j (from -9 to 8) and $P_{i,j,-9}$ is the price of the same bond on the end-of-window day ($t = -9$). The independent variable is day t, with t ranging from -9 to 8 (including $t = 0$), and $t = 0$ being the end-of-month day. The regression includes bond-window fixed effects. Standard errors are clustered at bond-window level and pair-window level. Standard errors are reported in parentheses. $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1) Bloomberg CBBT	(2) ECB executed	(3) TraX traded
-8	0.032	0.110***	0.090***
- 7	0.223***	0.139***	0.186***
- 6	0.272***	0.244***	0.267***
- 5	0.254***	0.214***	0.255***
-4	0.370***	0.279***	0.418***
-3	0.361***	0.420***	0.392***
- 2	0.363***	0.496***	0.430***
- 1	0.422***	0.525***	0.472***
0	0.510***	0.550***	0.490***
1	0.441***	0.371***	0.366***
2	0.323***	0.312***	0.329***
3	0.063	0.246**	0.243***
4	0.134	0.305***	0.090
5	0.235**	0.169*	0.204***
6	0.191*	0.219*	0.212***
7	0.067	0.118	0.138*
8	-0.136	-0.112	-0.114
Obs.	9,554	3,641	9,373
R^2	0.4799	0.5446	0.5205

Table A-V. Eurosystem purchases and bond yield changes around end-of-month - This table presents the interaction coefficients from a regression analysis where the dependent variable is the change in bond yield, specified as $Y_{i,j,t} - Y_{i,j,-9}$. In this expression, $Y_{i,j,t}$ represents the yield of bond i on day t within window j (ranging from -9 to 8), and $Y_{i,j,-9}$ refers to the yield of the same bond on the last day of the window ($t = -9$). The primary independent variable involves the interaction of a dummy variable, D.Purchase$_{i,j,t}$ (which equals one when bond i is purchased on day t within window j, and zero otherwise), and daily indicator variables. Standard errors are clustered at the bond-window level, and are indicated in parentheses. $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1) Base	(2) Base	(3) Base	(4) Base	(5) Without quarter-end	(6) Without quarter-end	(7) Without quarter-end	(8) Without quarter-end
-8	0.006*	0.008*	0.007*	0.007	0.007**	0.009*	0.009*	0.009*
-7	-0.006	-0.008	-0.007	-0.007	-0.007*	-0.009	-0.007	-0.007
-6	0.001	-0.004	-0.001	-0.001	-0.001	-0.006	-0.004	-0.004
-5	0.002	-0.005	-0.003	-0.003	-0.002	-0.010	-0.006	-0.006
-4	-0.008	-0.017***	-0.015***	-0.014**	-0.006	-0.015**	-0.012**	-0.012**
-3	-0.015***	-0.023***	-0.020***	-0.020***	-0.014**	-0.024***	-0.021***	-0.021***
-2	-0.020***	-0.024***	-0.021***	-0.021***	-0.020***	-0.025***	-0.021***	-0.022***
-1	-0.018***	-0.021***	-0.018***	-0.019***	-0.010*	-0.017**	-0.015**	-0.015**
0	-0.019***	-0.019***	-0.016**	-0.016**	-0.005	-0.010	-0.006	-0.007
1	-0.014**	-0.012*	-0.009	-0.009	-0.006	-0.005	-0.002	-0.003
2	-0.006	-0.003	0.000	0.000	0.007	0.009	0.012	0.011
3	0.004	0.006	0.008	0.008	0.023***	0.021**	0.024***	0.023**
4	-0.011	-0.004	-0.002	-0.002	0.004	0.010	0.012	0.011
5	-0.001	0.001	0.004	0.004	0.015*	0.018*	0.020**	0.019**
6	0.003	0.008	0.009	0.009	0.019*	0.021**	0.021**	0.021**
7	0.011	0.017*	0.018*	0.018*	0.024**	0.028**	0.029***	0.028**
8	0.031***	0.035***	0.035***	0.035***	0.043***	0.045***	0.044***	0.044***
Obs.	19,274	19,271	19,274	19,274	14,720	14,717	14,720	14,720
R^2	0.3965	0.5791	0.5646	0.5655	0.3759	0.5508	0.5357	0.5372
Bond FE	Yes	Yes	-	Yes	Yes	Yes	-	Yes
Window FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Window X Bond FE	-	Yes	-	-	-	Yes	-	-
Window X Maturity FE	-	-	Yes	Yes	-	-	Yes	Yes

Table A-VI. Competition and Frontloading: Eurosystem purchases and bond yield changes around end-of-month - This table exhibits the interaction coefficients from a regression analysis where the dependent variable signifies the bond yield change, described as $Y_{i,j,t} - Y_{i,j,-9}$. Here, $Y_{i,j,t}$ denotes the yield of bond i on day t within the window j (spanning from -9 to 8), and $Y_{i,j,-9}$ is the yield of the identical bond on the last day of the window ($t = -9$). The primary independent variable is the interaction between a dummy variable, D.Purchase$_{i,j,t}$ (which is set to one when bond i is purchased on day t within window j, and zero otherwise), and daily indicator variables. Standard errors are clustered at the bond-window level and are presented in parentheses. $***$, $**$, and $*$ indicate significance levels of 1%, 5%, and 10%, respectively.

	(1) Base	(2) Low counterparties	(3) Front loading
-8	0.008*	0.017*	0.003
-7	-0.008	-0.014	-0.013**
-6	-0.004	-0.009	0.004
-5	-0.005	-0.013	-0.001
-4	-0.017***	-0.032***	-0.001
-3	-0.023***	-0.028**	-0.042***
-2	-0.024***	-0.025**	-0.013
-1	-0.021***	-0.026**	-0.016
0	-0.019***	-0.017	-0.012
1	-0.012*	0.006	0.017
2	-0.003	-0.003	0.019**
3	0.006	0.016	0.028*
4	-0.004	0.020	-0.011
5	0.001	0.025	0.014
6	0.008	0.034*	0.049**
7	0.017*	0.041*	0.065***
8	0.035***	0.068***	0.072***
Obs.	19,271	6,389	3,657
R^2	0.5791	0.6192	0.4483
Bond FE	Yes	Yes	Yes
Window FE	Yes	Yes	Yes
Window X Bond FE	Yes	Yes	Yes

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