Central Bank–Driven Mispricing*

Loriana Pelizzon Marti G. Subrahmanyam Davide Tomio Jun Uno

Abstract

We show that bond purchases undertaken in the context of quantitative easing efforts by the European Central Bank created a large mispricing between the market for German and Italian government bonds and their respective futures contracts. On top of the direct effect the buying pressure exerted on bond prices, we show three indirect channels through which the scarcity of bonds, resulting from the asset purchases, drove a wedge between the futures contracts and the underlying bonds: the deterioration of bond market liquidity, the increased bond specialness on the repurchase agreement market, and the greater uncertainty about bond availability as collateral.

Keywords: Central Bank Interventions, Liquidity, Sovereign Bonds, Futures Contracts, Arbitrage.
JEL: G01, G12, G14.

*Research Center SAFE - Goethe University Frankfurt and Ca' Foscari University of Venice, Stern School of Business at New York University, Darden School of Business at University of Virginia, and Waseda University, respectively. We thank the Einaudi Institute of Economics and Finance, the NYU Stern Center for Global Economy and Business, the NYU-Salomon Center, the Volkswagen Stifftung Europe and Global Challenges Project, and the SAFE Center, funded by the State of Hessen Initiative for Research, LOEWE, for their financial support. Subrahmanyam also thanks the Anneliese Maier Research Award of the Alexander von Humboldt Foundation for generous support and the London Business School for its hospitality. We thank the anonymous market participants from global financial institutions, as well as the Treasury officials and central bankers we met, for sharing their thorough understanding of the institutional details of the Euro-zone sovereign bond market with us. We are also indebted to Darrell Duffie, Marco Fanari, Peter Feldhütter, Kenneth Garbade, Sven Klingler, Stefano Iacobelli, Francis Longstaff, Narayan Naik, Christopher Neely, Anna Pavlova, Angelo Ranaldo, Lucio Sarno, Stephen Schaefer, Jeremy Stein, Roberto Violi, Haoxiang Zhu and participants in seminars at the London Business School, the Cass Business School, the Einaudi Institute for Economics and Finance, the Bank of Italy, the Office of Financial Research, and at the Fifth International Conference on Sovereign Bond Markets at the Bank of Canada for helpful comments. The views expressed in the paper are those of the authors and not attributable to the financial sponsors. Corresponding author: Loriana Pelizzon, pelizzon@safe.uni-frankfurt.de.

I Introduction

Open market operations—specifically, the outright purchase of securities by central banks—are a traditional tool of standard monetary policy, employed by central banks to lower the level of interest rates, stabilize a volatile interest rate and/or foreign exchange market, and instill trust in the economy among market participants. The period following the Great Recession, and the European Sovereign Bond crisis that ensued, has witnessed central banks expanding their toolbox, envisioning new, non-standard operations targeting wide swaths of the bond market, generally referred to as quantitative easing (QE). Between March 2015 and April 2017, when our sample ends, the European Central Bank (ECB) has purchased €50 to 80 billion worth of sovereign bonds a month, in the context of its so-called Public Securities Purchase Programme (PSPP).[1]

The principal objective behind central banks' open market operations is most often to change interest rates and, more generally, the cost of money in the economy. Notwithstanding the final goal of affecting prices and due to their remarkable size, central banks' operations are susceptible to having "unintended consequences," affecting the proper functioning of the markets that they are targeting. In an effort to mitigate the unwanted effects, central bank interventions such as the ECB's QE are engineered to be "market neutral," aiming to preserve the price discovery mechanisms at play in the functioning of financial markets, keeping them free from mispricing or arbitrage and preserving the law of one price.[2] In other words, the ECB intended that the bond purchases affect the *absolute* level of interest rates—as the central bank explicitly aims at detaching them from the "natural" level they would have been at had the intervention not taken place—but without affecting its *relative* level across assets. Thus, the price discovery process determining interest rates in

[1]Similarly, the Bank of Japan has acquired between ¥2 and 10 trillion a month worth of Japanese government bonds since February 2009, the Federal Reserve System purchased $1.2 trillion worth of US Treasury bonds between March 2009 and September 2011, and the Bank of England purchased £463 billions worth of UK Gilts between March 2009 and December 2017. These interventions are unprecedented in the history of central banking, in terms of their magnitude and breadth of coverage.

[2]The ECB states that it specifically designed its QE program—the intervention we consider in this paper—to be "market-neutral," as exemplified by the speech with which Benoît Cœuré (2015), a member of the ECB's Executive Board, first outlined the guidelines for the ECB's QE:

> *"One key principle [...] of the PSPP is the minimisation of unintended consequences. This can be ensured by obeying the concept of market-neutrality of our operations[, that is,] while we do want to affect prices, we do not want to suppress the price discovery mechanism."*

We interpret this statement as affirming the ECB's intention to not "suppress the price discovery mechanism"—that is, to keep the market free from mispricing or arbitrage, preserving the law of one price.

equilibrium is not to be hindered by the conduct of the central bank, and its actions ought not to generate mispricing between assets. In this paper, we investigate the following questions: Were the actions of the ECB indeed market neutral? What effect did the bond purchases, of unprecedented size, undertaken as part of the QE by the ECB have on the bonds' *relative* pricing?

To answer these questions, we focus on one of the most straightforward arbitrage relationships in the fixed-income realm: that between the cash bond and corresponding futures contract. We show that the mispricing between cash bonds and the futures contract caused by the ECB intervention was as high as €0.45 per €100 worth of bonds, corresponding, for example, to over three-quarters of a billion euros of market dislocation in the over €200 billion market for German and Italian futures contracts, in each quarter. We summarize the main takeaway of our findings in Figure 1, where we present the mispricing between futures and bonds, in percentage terms (left axis), in relation to the fractions of bonds outstanding held at the ECB as a result of the QE (right axis).[3] We show the quantities for Italy and Germany, the two countries we analyze, in Panels A and B, respectively. While we derive the mispricing quantities and study the channels through which the central bank affected the futures-bond basis in extensive detail in the paper, Figure 1 shows summarily that, as the ECB increased its holding of bonds at a pace of €50 to 80 billion a month during the period of our analysis, it drove a significant wedge between the price of the futures contracts and that of the underlying bonds (i.e., it affected the bonds' *relative* pricing).

Insert Figure 1 here.

In our analysis, we account for the three costs that an arbitrageur would face when taking advantage of the relative mispricing: i) transaction, ii) borrowing, and iii) rollover costs. We then show that the mispricing is still present in the market even after these adjustments, indicating the level of actual trading profits arbitrageurs effectively left untapped. Transaction, borrowing, and rollover costs (the last two involving the repo market) represent the channels through which the bond scarcity resulting from the ECB purchases affected arbitrage activity. In fact, they are the quantities that Cœuré (2015) specifically mentions, while setting out the guidelines for the QE PSPP intervention, as those the ECB is concerned with in its effort to ensure the market neutrality of its operations:

[3]By percentage terms, we mean that we normalize the absolute mispricing between bonds and futures contract by the notional amount of the futures contract, and by accounting for the remaining time to delivery of the contract. We detail the calculations behind this figure in Section V.

> *"We will operationalise this principle [of market neutrality] by ensuring a high degree of transparency around our interventions and by closely monitoring their impact on* ***liquidity and collateral availability****. [...] The preservation of market liquidity can be considered as a prerequisite for the proper working of the portfolio rebalancing channel that is at the heart of our asset purchase programmes. To this end, we will take particular care* ***to avoid exacerbating any existing market frictions****. More specifically, we will try to avoid, to the extent possible, purchasing specific securities such as current cheapest-to-deliver bonds underlying futures contracts, securities commanding 'special' rates in the repo market as a sign of temporary scarcity, and other assets displaying significant liquidity shortages."* [Emphasis added]

This quote indicates that liquid bond markets and a well-functioning repo market were uppermost in the central bank's concerns when it planned the QE intervention. To examine the validity of this statement, we show that the bond scarcity following the ECB's QE impaired the functioning of the repo market by making bonds more expensive to obtain there, and at more uncertain rates. Moreover, the quote indicates that exacerbating the futures-bond arbitrage gap was of particular concern to the ECB, thus motivating the specific mispricing we focus on in our analysis.

The ameliorative effects that unconventional monetary policy interventions had on the *absolute* level of interest rates have been the object of the extant academic literature (Krishnamurthy and Vissing-Jorgensen, 2011; Joyce, Lasaosa, Stevens, and Tong, 2011; Gagnon, Raskin, Remache, and Sack, 2011; Christensen and Rudebusch, 2012; D'Amico and King, 2013; Bauer and Rudebusch, 2014; Eser and Schwaab, 2016; Ghysels, Idier, Manganelli, and Vergote, 2016; Krishnamurthy, Nagel, and Vissing-Jorgensen, 2017; De Santis and Holm-Hadulla, 2017; De Pooter, Martin, and Pruitt, 2018; Song and Zhu, 2018b). In the literature on central bank intervention, a key concern has been establishing a counterfactual: What would the *absolute* level of the bond yields have been had the central bank not intervened? In contrast, we have no need to explicitly define a counterfactual to show the unintended consequence that the ECB's QE had on the *relative* level of interest rates, since the futures contracts serve as a direct metric for comparison. We investigate whether, by purchasing only one category of assets (i.e., cash sovereign bonds) and focusing on lowering the *absolute* level of interest rates, the ECB displaced *relative* interest rates across assets, in particular decoupling the cash bond market from its futures market counterpart. While any statement on the effect of QE interventions on the absolute level of interest rates would require us to explicitly define a counterfactual term structure based on a non-trivial set of often-untestable assumptions—regarding, among others, market participants' risk aversion, monetary policy beliefs, and expectations, and the preferred habitat of investors—testing for deviations in relative prices only requires the presence of an arbitrage such as the one we consider in this paper, a much weaker requirement.

To show the divergence of relative interest rates/bond prices, we select one among the lowest-cost arbitrages in the fixed-income world, namely that between a futures contract and its underlying sovereign bond. Such an arbitrage is the ideal setting to test for the presence of relative interest rate misalignment for a cohort of reasons. First, it is simple to execute: a trader establishes a long position in a single security and a short position in another. The two perfectly offsetting positions are made in a single security each—compared to, for example, a portfolio of positions involved in a term structure arbitrage—while ensuring that the trader is fully hedged. Second, the securities involved in the arbitrage are traded in exchanges rather than over the counter, meaning that we have firm, tradable quotes on which to base our potential profit calculations, unlike arbitrage trades involving other derivatives (e.g., the basis trade between a corporate credit default swap and the bonds issued by its underlying company). Third, the pricing relationship between the cash bond and the futures contract is a textbook case of arbitrage, which is obtained under almost no strong assumptions, and not a statistical "near-arbitrage." The simplicity of the trade allows us to identify all channels through which the central bank intervention could affect the mispricing, and to test whether it, in fact, does. While the ECB intervention might have created mispricing between other assets, we concentrate, for all these reasons, on the sovereign cash bond-futures arbitrage, which allows us to make a statement that—since it holds for a low-cost, rigorously defined arbitrage—can be generalized to less obvious arbitrages that might involve even higher costs.[4]

We identify an indicator of the suppression of the price discovery mechanism as the presence of a mispricing between the bond and futures prices, and relate this indicator to the ECB's bond purchases. In the first part of our analysis, we do not require that the mispricing be tradeable—that is, we explicitly distinguish between mispricing and the existence of an arbitrage opportunity. Mispricing is symptomatic of the possibility that the price discovery process is impeded, in that

[4]While we aim to consider a low-cost arbitrage, we also want to ensure the robustness of our results. To do so, we take a conservative approach in estimating the arbitrageur's total costs, and assume that the arbitrageur faces the *highest* trading costs, paying the bid-ask spread in the bond trade as well as in the futures trade, which would not necessarily be the case if she could obtain the securities at a price closer to the midpoint (for example, from one of her customers as a bond dealer). Moreover, we effectively "inflate" the frictional costs by assuming that the arbitrageur needs to borrow the bond in order to short it, and go long the futures contract instead of assuming that she could sell a bond she might already own.

market participants can only assess that the "true price" of the bond lies between the midquote of the bond and that of the futures contract, instead of identifying it as a single point-estimate. However, trading, borrowing, and rollover costs may all prevent an arbitrageur from taking advantage of the mispricing. An arbitrage opportunity, on the other hand, consists of the possibility that a trader can *actually* take advantage of the mispricing, and that her trade is profitable, once all costs are taken into consideration: A mispricing relationship is, therefore, a necessary but not sufficient condition for an arbitrage opportunity. While showing the presence of arbitrage opportunities, as we do, documents the utmost example of the failure of the law of one price, analyzing the mispricing is an important first step because i) we attribute conservatively high costs to the arbitrageur's trade—assuming that she does not own bonds, that she obtains them on the repo market, and that she pays the bid-ask spread on both her bond and futures transactions—hence the true estimate of market dislocation lies somewhere between the mispricing and the arbitrage opportunity we document; ii) the efficacy of central bank intervention relies on markets' functioning well, and the presence of a mispricing—although one that does not necessarily lead to arbitrage opportunities—translates into a heightened sense of market participants' uncertainty about the true values of assets; and, finally, iii) the costs of QE interventions and the resulting negative welfare implications increase in how much the ECB overpays for the assets it purchases: the mispricing measure, ignoring transaction and borrowing costs, therefore, represents a better estimate of such overpayment than the actual arbitrage opportunities created, since the ECB could have obtained bonds with auctions rather than in the open market, as arbitrageurs would need to. In the remainder of the paper, we first analyze the mispricing between bonds and futures, and later show what fraction of it represents actual arbitrage opportunities.

Finding arbitrage opportunities in markets for liquid securities raises the question of what further frictions may exist that explain their presence and that are not directly accounted for in the calculated foregone arbitrage profits. In the discussion of our findings, we hypothesize that the constraint we do not observe is one that affects the balance sheet and capital requirements of market participants: specifically, the leverage ratio detailed in the Basel III regulation. Our hypothesis is consistent with the similar argument put forward by Du, Tepper, and Verdelhan (2018), who show that the magnitude of the deviations from the covered interest rate parity they uncover is consistent with the strictly positive returns that financial institutions would demand on a riskless trade, if their leverage ratio was binding, i.e., if they were abiding to the non-risk-weighted capital requirements detailed in Basel III. We believe that the leverage ratio plays a similar role in our setting. (Fleckenstein and Longstaff, 2018, take the inverse, but entirely consistent, approach to ours, *inferring* balance sheet costs starting from mispricing data based on the same kind of arbitrage trade we consider, albeit in the setting of the US Treasury market.) It is unlikely, however, that the leverage ratio by itself could explain the emergence of arbitrage opportunities after March 2015: In the current or a previous form, the leverage ratio requirement was in place throughout our sample, that is, even before the QE intervention by the ECB, when no arbitrage opportunity is observed. We thus postulate that the mispricing we document is the result of two contemporaneous events: (1) the buying pressure and market dislocations following the ECB's bond purchases, and (2) the regulatory capital constraints implying non-negative minimum required returns on riskless trades, because of the regulatory capital they employ. We posit that, if no capital constraints were imposed on financial institutions, arbitrageurs would eliminate any temporary mispricing resulting from the central bank's actions; conversely, without any central bank intervention, no major disruption would lead to a systematic failure of the price discovery process in the markets.

We postulate the conditions for the feasibility of truly market-neutral central bank interventions: central banks need to take over the market's function of enforcing the price discovery mechanism by purchasing *both* bonds and the derivative contracts that have the bonds as their underlying asset; alternatively, central banks can decide to purchase a single asset, displacing interest rates, and rely on market participants to close the interest rate pricing gap. The precondition for market participants to be able to effectively enforce arbitrage-free relative pricing and ensure the smooth functioning of the price discovery mechanism, however, is that their regulatory capital is not constrained. Thus, interventions targeting a single asset class cannot be market neutral if capital constraints bind the arbitrageurs. In conclusion, we offer a simple policy implementation strategy that would improve QE's welfare impact, attenuating the relative mispricing of bonds even in the presence of capital-constrained financial intermediaries.

The mispricing we observe in the futures-bond arbitrage and others akin to it should concern central banks, and regulators in general, for two reasons. First, central banks value the informativeness of financial markets (Cœuré, 2015): the market for interest rates should be informative, and it is in the policy makers' interest to ensure that market participants agree on what the correct interest rate is. Even a small amount of uncertainty regarding the level, slope, and curvature of the yield curve would translate into substantial capital at risk, as Euro-zone sovereign bonds have an outstanding amount of €10 trillion, and are widely used as collateral in bond spot and derivative markets based on their having open interests that measure in the billions. Second, governments and central banks are sensitive to welfare considerations: the ECB's intervention's effect of widening the gap between the prices of the two securities and allowing traders to profit from selling the more expensive security—and contemporaneously perfectly hedging it by buying the cheaper security—is tantamount to a direct transfer from taxpayers to arbitrageurs (i.e., financial institutions), and hence a matter for policy concern.

The paper is organized as follows. In Section II, we highlight the papers our work is most closely related to and our contribution to the literature. In Section III, we provide a brief overview of the functioning of the ECB's QE. We describe the data sources we employ and the details of the futures contract in Section IV. Section V presents the particular trade we study in detail and shows that it cannot be profitable in a frictionless market. We present our results in Sections VI and VII, where we detail the market frictions that are involved in the trade, argue what effects the QE had on them, and show that, after taking into account all relevant costs, a sizable arbitrage is still present on the market as a result of the intervention by the ECB. We discuss our results in Section VIII, where we argue that the required rates of return on arbitrage trades, as implied by regulatory constraints, are higher than the arbitrage profits we compute, potentially explaining the existence of the mispricing. Finally, we recommend an alternative asset purchase strategy that would diminish the mispricing caused by the QE and the resulting impact on welfare. We conclude in Section IX.

II Literature Review

The extent of central banks' unconventional monetary policies has fostered a recent strand of literature that focuses on their unintended consequences, ranging from the effect on bond market liquidity (Pelizzon, Subrahmanyam, Tomio, and Uno, 2016; Pelizzon, Subrahmanyam, Tobe, and Uno, 2017; Schlepper, Hofer, Riordan, and Schrimpf, 2017; Christensen and Gillan, 2018), to the functioning of the repo markets (D'Amico, Fan, and Kitsul, 2015; Corradin and Maddaloni, 2017), to the QE's effect on the real economy (Acharya, Eisert, Eufinger, and Hirsch, 2017; Crosignani, Faria-e Castro, and Fonseca, 2017; Daetz, Subrahmanyam, Tang, and Wang, 2017). We contribute to this developing strand of literature by analyzing the effect of QE interventions on the actual arbitrage relationship and the mispricing between the assets the central bank is heavily purchasing and another prominent asset class. We identify the channels through which the intervention indirectly affects this mispricing and analyze the effects of QE on these channels.

Recent papers in the same strand of literature that are closest to ours in spirit are Pasquariello

(2017) and Corradin and Rodriguez-Moreno (2016). Pasquariello (2017) contributes to the literature by developing a model showing that, unless markets are perfectly integrated or noise traders split their trades equally across markets, government interventions as outright purchases of assets following a private price target cause mispricing between two otherwise identical assets. The paper includes an empirical analysis relating interventions on the foreign exchange market to observed deviations between the returns of stocks listed abroad and their respective American depository receipts (ADRs). The underlying theoretical model formalizes the important intuition about the nature of arbitrage in the context of government interventions, and thus is in line with our findings: the ECB never disclosed its price target for the purchased bonds or the quantity and timing of its purchases, thus causing a mispricing between otherwise identical assets. The bond market we investigate, in fact, was the *direct* object of the QE intervention and its pricing was the actual target of the ECB, which was held as private information. The market for ADRs, on the other hand, was tangentially affected by interventions in the foreign exchange market, and was arguably outside the remit of central banks when they designed their interventions. Moreover, we see our paper as complementing that by Pasquariello (2017) by proposing, on top of the direct channel, the indirect channels through which QE interventions can contribute to the mispricing of bonds, the assets most often used in open market interventions, and investigating and quantifying the effect bonds' scarcity has on these channels. Finally, the granularity of our high-frequency data and the availability of the aggregate bond quantity purchased by the ECB allow our analysis to attain a level of detail that would be unattainable when considering interventions on the foreign exchange market.

Corradin and Rodriguez-Moreno (2016) look at the differential in valuation between euro- and dollar-denominated sovereign bonds, studying how it is affected by the eligibility of the dollar-denominated bond at the ECB collateral pledging facility, and showing that bonds that are eligible as collateral are valued more highly by investors. Our paper differs significantly from that of Corradin and Rodriguez-Moreno (2016): the trade they analyze is a statistical arbitrage, since the maturity dates of the bonds are not necessarily aligned, and the foreign exchange swap employed in the trade does not have provisions protecting the buyer from depreciation on default—which, since sovereign default is correlated with that country's currency depreciation, would leave the investor unhedged in some states of the world.[5] Moreover, the unconventional monetary policy

[5]See Augustin, Chernov, and Song (2018) and Lando and Nielsen (2018) for recent work explaining why the spreads differ for sovereign CDS contracts quoted in different currencies, based on the correlation between sovereign default and currency depreciation.

they consider, the Long-Term Refinancing Operation (LTRO), did not include the outright purchase of sovereign bonds typical of QE interventions, and hence affected the pricing of the bond market only indirectly. Finally, the statistical arbitrage they consider involves multiple transactions in the bond market, the interest rate swap market, and the foreign exchange market: employing Bloomberg quote data for the bond prices and midquotes for the swaps rates does not necessarily provide a reliable measure of the actual profitability of the trades they consider. Buraschi, Menguturk, and Sener (2014) consider the same statistical arbitrage trade between bonds in different currencies as Corradin and Rodriguez-Moreno (2016) and show that the mispricing decreased for the currencies for which the FED extended global dollar swap lines. In the same strand of literature on mispricing, Du et al. (2018) analyze deviations of the covered interest rate parity and focus on how it is affected by bank capital requirements, which we tangentially touch upon in the discussion of our results.[6]

III ECB Interventions

The ECB's monetary intervention as a response to the 2007–2009 global financial crisis and the Euro-zone sovereign crisis of 2010–2012 has taken many forms, ranging from the jawboning and formal guidance by its board members, in particular its president, to the injection of liquidity into the major banks in the Euro-zone (through fixed-rate tender, full-allotment), and even to direct purchases of sovereign and corporate bonds in the cash markets. During the Euro-zone crisis, the policy interventions by the ECB consisted of (i) the Security Market Program (SMP), initiated in May 2010; (ii) LTRO, announced and implemented in December 2011; (iii) policy guidance, including the famous "whatever it takes" speech by Mario Draghi on July 26, 2012, which unveiled the potential for new tools to ease the European sovereign debt crisis; and (iv) Outright Monetary Transactions (OMT), announced in September 2012.

In a context of continuing near-deflationary conditions, and in a dramatic change of policy, the ECB announced in January 2015 a prolonged period of QE—a large-scale asset purchase program focused on government bonds, the PSPP—with the stated goal of generating inflation. The PSPP involved bond purchases commencing in March 2015, with an expected balance sheet expansion of more than €1 trillion in the following 18 months. The program began on March 9, 2015 and

[6]Contributing to the literature on mispricing in fixed-income markets, Feldhütter (2012) shows that corporate bonds can trade contemporaneously at different prices, depending on the identity of the buyer, with large traders trading at better prices.

was scheduled to last up to September 2016, but has since been prolonged multiple times and is currently slated to end in 2018. The program consists of monthly purchases of public and quasi-public securities, initially at the rate of €50 billion a month, which was increased to €80 billion between April 2016 and March 2017, when it was scaled back to €50 billion. The scale, scope, and duration of the PSPP is unprecedented in the ECB's—or, for that matter, central banks'—history: as a mean of comparison, the SMP, the most comparable intervention among those listed above involved purchases of about €218 billions, conducted over few months, and only targeting the bonds of troubled economies (i.e., Greece, Ireland, Spain, Portugal, and Italy).[7]

The monthly euro amount available for bond purchases is allocated across countries to reflect each country's national central bank's relative participation in the ECB's capital, which roughly corresponds to the proportion of the Euro-area GDP made up by the economy of that country. Within each country, the amount is split across bonds according to their amount outstanding (Cœuré, 2015). The ECB does not disclose further details on the modality or the timing of the purchases (that is, for example, on whether all bonds are purchased every month or whether the set of purchased bonds differs across months) or the specific amounts of daily purchases, contrary to the FED or the Bank of Japan, but reported that the bond purchases took place via direct acquisition in the secondary market—contrary to what was done by the FED and Bank of Japan, both of which largely acquired assets via reverse auctions (Song and Zhu, 2018b).

Panel A of Figure 2 shows the monthly amount of bond purchases for the two countries we analyze, Germany and Italy, in billions of euros, according to data obtained from the ECB. Each month, the ECB purchases, on average, €9 (13) billion worth of Italian (German) bonds. To place this amount in perspective, the outstanding amount of Italian debt at the end of 2014 was €1.8 trillion, and the corresponding figure for Germany was €2.1 trillion.[8] It follows that, after two years of QE, where our dataset ends, the ECB held €$9 \cdot 24 = 216$ billion worth of Italian bonds, or about 12% of the amount outstanding, and €$13 \cdot 24 = 312$ billion worth of German bonds, or 15% of their outstanding amount.[9] Accordingly, Panel B of Figure 2 shows the percentage of

[7]Eser and Schwaab (2013) show that the SMP lowered the level and volatility of yields in the targeted countries, focusing on how the intervention differs from other outright bond purchases by central banks. Ghysels et al. (2016) and De Pooter et al. (2018) also assess the effect of SMP on bonds' yield, liquidity, and volatility, and provide details on the SMP execution.

[8]The breakdown of the monthly purchase quantities and duration by country can be found at `https://www.ecb.europa.eu/mopo/implement/omt/html/index.en.html`. We obtain data on the amounts of government debt outstanding from the central banks of Italy and Germany.

[9]The ECB purchased both central and local government bonds. For Italy, local bonds make up a minuscule amount

sovereign bonds held by the ECB in the 2013–2017 period, as a fraction of their overall issued amount. Panel B shows clearly the steady increase in sovereign bond holdings at the ECB, and suggests the growing scarcity in bond availability resulting from the intervention.

Insert Figure 2 here.

IV Data Sources

In this study, we employ high-frequency data on the prices and traded quantities of Euro-zone bonds and futures contracts for the 2013–2017 period, which encompasses three years of QE intervention by the ECB, the calendar years 2015 to 2017, and two control years, the calendar years 2013 and 2014. We identify mispricing opportunities between futures and the underlying bonds for contracts written on Italian BTP (Buoni del Tesoro Poliennali, or Treasury Bonds) bonds and German Bunds (Bundesanleihen, or Federal Bonds).[10] We focus on two countries: Germany is a so-called "core" country, and Italy belongs to the European "periphery." Our concern is to confirm that our findings are not driven by country-specific idiosyncrasies. The datasets of cash bond and futures prices we employ are time stamped at the millisecond level, allowing us to quantify foregone arbitrage profits at any point in time during the trading day, avoiding problems of non-synchronicity that several prior studies faced.

IV.A The Cash and Repo Bond Markets

Price and volume data for the cash sovereign bonds are obtained from the MTS Group. The MTS trading system is an automated, quote-driven electronic limit order interdealer market, in which market makers' quotes can be hit or lifted by other market participants via market orders. The dataset we analyze in the present study is by far the most complete representation of the Euro-zone sovereign bond market available: our data consist of all real-time millisecond-stamped quotes, orders, and transactions that took place on the MTS European sovereign bond market.[11]

of the total purchased. For Germany, on the other hand, local government bonds make up about a quarter of all public debt. The ECB purchased the same relative amount of central and local debt.

[10]While two other Euro-zone countries, France and Spain, also have traded futures contracts, their markets are significantly less developed and less liquid than their Italian and German counterparts. Furthermore, futures contracts for Spanish government bonds were first introduced only in late 2015.

[11]We direct the interested reader to Pelizzon, Subrahmanyam, Tomio, and Uno (2016) for a thorough description of the functioning, structure, and market share of the MTS market.

To study the determinants of the mispricing between bonds and futures, we need measures of the costs involved in funding arbitrage positions, including the cost of borrowing/shorting a bond. We employ the overnight Euro OverNight Index Average (EONIA) as a first proxy for the riskless rate, and the cross-currency basis swap spread between euros and dollars as a measure of the dollar–funding liquidity needs of European financial institutions (Pelizzon et al., 2016). Both rates are obtained from Bloomberg. For a more precise estimate of the cost of borrowing a bond, rather than using the market-wide riskless rate, we employ the cost of doing so through a repurchase (repo) transaction in Subsection VI.D. The two largest special repo platforms for euro-denominated sovereign securities are the MTS Repo platform, operated by the MTS Group, and the BrokerTec platform, of the NEX Group. We obtain data detailing all special repo transactions taking place on the MTS Repo platform, including their rate, timing, term, and settlement. We also employ the RepoFunds rate (RFR) index, a daily index published jointly by BrokerTec and MTS, which is a quantity-weighted average of all special and general collateral (GC) transactions involving German or Italian bonds. We use the RFR index for robustness purposes, and to verify that the transactions taking place on the MTS platform are representative of the overall repo market.

IV.B The Futures Market

A government bond futures contract is an exchange-traded instrument—a contractual obligation—whereby the seller of the futures contract agrees to deliver a bond to the buyer, on or before the delivery date, and the buyer agrees to pay a price (agreed on the date of the trade) upon delivery. On each trading day following the trade, the trading positions are marked-to-market. The seller can deliver any bond from a basket of deliverable bonds, for a total (adjusted) face value of €100,000. For instance, for the long-term bond futures contracts of Italy and Germany, the two countries that are the focus of our analysis, the contract terms specify that a delivery obligation arising from a short position on a long-term contract may only be fulfilled by the delivery of coupon-bearing debt securities issued by the central government of Italy (Germany), with a remaining life of between 8.5 and 11 (10.5) years and an original maturity of no longer than 16 (11) years.[12] The bonds that are eligible to be delivered into the futures contract can, therefore, differ markedly as to their coupon and time to maturity, and, therefore, their price. To obviate the seller's incentive to short-change the

[12]There are also futures contracts on the short- and medium-term bonds (i.e., bonds with time to maturity of between two and five years) traded on the Eurex. However, these contracts tend to be much less liquid in general, and are therefore not analyzed here.

buyer by delivering a bond that is substantially cheaper than the others, the futures contract buyer will only pay a certain proportion of the agreed-upon price, specific to the bond that is actually delivered. This bond-specific proportion—its conversion factor—is determined as the price (as a fraction of face value) that the bond would have at delivery if the term structure was flat at 6%.[13] While conversion factors are meant to level out the price differences between deliverable bonds, for every futures contract, one of the bonds can generally be identified as the one that the futures seller is most likely to deliver (since it costs less, taking into account its current market price in relation to the conversion factor), and is thus referred to as the cheapest-to-deliver (CTD) bond. Which of the deliverable bonds is CTD depends on a host of factors ranging from supply- and demand-side considerations—for example, whether the bond is in abundant supply or is an on-the-run issue, and the level and slope of the bond yield curve in relation to the notional yield and coupon rate.

The price difference between every deliverable bond relative to the futures contract price can qualify as a basis; yet, in the remainder of the paper, when we refer to the mispricing between the bonds and the futures contract, we mean the basis of the bond that the short position will likely deliver: the CTD. Further details on the identification of the CTD bond can be found in Section A.1 of the Appendix and in Merrick Jr, Naik, and Yadav (2005).[14] Futures contracts have deliveries on a quarterly basis: in March, June, September, and December. While three futures contracts with up to nine months to delivery may be traded at any point in time, we focus in this study on the nearest delivery because this is generally the most liquid contract. The basic observation unit in our sample, therefore, is the nearest-delivery futures contract–CTD bond pair for country i and day t. Our sample covers 17 contracts per country and their corresponding CTD bonds.[15]

Our bond futures data are obtained from Reuters and encompass all trades and quotes for futures contracts on long-term coupon-bearing bonds from Eurex, a major stock and futures exchange

[13]For the September 2016 BTP futures contract, for example, four bonds could be delivered. The smallest coupon rate among the deliverable bonds was 1.5% and the largest was 4.5%. Obviously, the two bonds had widely different prices, which were reflected in their respective conversion factors of 0.702604 and 0.898551. The bond with the larger coupon would have a larger price if the yield curve was flat at 6%, therefore commanding a larger conversion factor and a larger payment from the futures long position holder. That is, a futures seller that delivered the more expensive bond with the more sizeable coupon would receive an invoice about 27% larger.

[14]The CTD bonds are clearly identified in our sample, having the lowest basis for the vast majority of the time. We determine the CTD bond as that which most frequently has the lowest basis. The median frequency across contracts that the bond we identify as CTD has the lowest basis is 99.72% of the time for Italy, and 99.84% for Germany. Section A.1 of the Appendix elaborate on the identification of the CTD bonds.

[15]While every futures contract has a single CTD bond, the same bond can be CTD for several consecutive contracts. Our sample of CTD bonds consists of six distinct bonds for Italy and ten for Germany.

owned by the Deutsche Börse group. Eurex offers traders a continuous electronic trading platform, where liquidity is provided by market participants.[16] In contrast to cash sovereign bonds, Euro-zone government bond futures contracts only trade on exchanges, namely on the Eurex and, more sparsely, the Intercontinental Exchange (ICE). The coverage of our data on futures contracts, therefore, is almost complete.[17] Subsection IV.B offers a primer on the functioning of government bond futures contracts, and further details are covered in Section A.1 of the Appendix. Descriptive statistics for all variables employed in our analysis are presented in Table VIII, in Section A.2 of the Appendix.

V The Future-Bond Basis

To make a statement on the value of the cash bonds *relative* to the futures contract, we need to define the mispricing (i.e., the difference between the price of the bond and a replicating portfolio made up of the futures contract). We calculate the arbitrage profits an arbitrageur would have locked in if she were to short the CTD bond and go long the corresponding futures contract. The arbitrage strategy, at a time t before contract delivery T, is as follows:

1) At time t: The arbitrageur acquires the CTD bond via reverse repo, agreeing to sell it back at delivery date T at a premium determined by the repo rate r_t,
2) At time t: The arbitrageur sells the bond at the price B_t and is compensated for the coupon A_t accrued from the previous coupon date,
3) At time t: The arbitrageur goes long on the futures contract, agreeing to pay, at delivery, F_t, adjusted by the conversion factor CF, and the coupon A_T accrued up to delivery,
4) At time T: The arbitrageur receives the CTD bond from the futures seller,
5) At time T: The arbitrageur delivers the CTD bond to the repo buyer.

Taking into account the conversion factor, the coupon the CTD bond accrues between the trade date and delivery into the futures contract, and the gains from the repo transaction, we calculate the

[16] A trivial explanation for the mispricing we observe could be that the cash and futures markets for sovereign bonds are highly segmented. However, that is not the case as most major financial institutions are dealers in—and thus have access to—the MTS cash bond market (AFME, 2012) and every large trader has access to the Eurex sovereign bond futures market.

[17] To the extent our data are less than complete, the quotes we use would be conservative and the arbitrage opportunities we identify would be biased downward.

basis for day t and trading minute m as:

$$Basis_{m,t} = \underbrace{\left(B_{m,t} + A_{i,t+2}\right)\left(1 + \frac{T-(t+2)}{360} r_t\right) - A_T}_{\text{Forward Bond Price}} - \underbrace{F_{m,t} \cdot CF}_{\text{Futures Equivalent Price}} \tag{1}$$

where $B_{m,t}$ is the price of the CTD bond on day t, at trading minute m, $F_{m,t}$ is the futures price, CF is the conversion factor for the CTD bond, $\frac{T-(t+2)}{360}$ is the maturity of the term repo, considering a $t+2$-day settlement for the underlying bond, multiplied by the repo rate at time t, r_t is the interest rate earned by the arbitrageur on the reverse-repo transaction, A_{t+2} is the coupon accrued from the last payment before settlement until the trade settlement date $t+2$, and A_T is the coupon accrued from the last payment before settlement until delivery.[18] The basis is calculated in euros per €100 of bond face value. In the remainder of the paper, we calculate the daily variable, $Basis_t$, as the average mispricing across the 380 trading minutes of the particular trading day, $Basis_t = \frac{\sum_{m=1}^{380} Basis_{m,t}}{380}$. The basis we calculate assumes that it is certain which bond is the CTD. More realistically, the short futures position includes the optionality of delivering whichever bond is cheapest at the delivery date. The option is more and more valuable the closer bond yields are to 6%, as explained in Section A.1 of the Appendix. During the time period we consider, yields are far away from that level, making the value of this optionality negligible. Moreover, the mispricing we observe increases as yields decrease (i.e., as the value of the optionality decreases), ruling out the possibility that this quality option is a significant driver of our findings.

Figure 3 shows the time series of $Basis_t$ (the mispricing per €100 of bond face value) between January 2013 and April 2017 for German and Italian futures contracts, in yellow and green, respectively. The QE period is shaded in gray and starts in March 2015. In this first approximation of the mispricing between cash bond and futures, we take the naïve approach of calculating the basis using the midquote of bond and futures prices, assuming that the bonds and futures contracts can be traded at a better price than that indicated by the bid- and ask-quotes, and that the bond can be borrowed at the risk-free rate, which we approximate with the EONIA rate. This approach allows us to compare the mispricing between bonds and futures to the arbitrage opportunities between the two assets. That is, we can separate the *direct* effect of the ECB intervention on the mispricing—the relative increase in bond prices compared to their futures counterpart following the central bank's

[18]The inclusion of A_{t+2} and A_T accounts for the possibility that coupons are paid between settlement of the cash leg and settlement of the futures leg.

large bond purchases—and the *indirect* effects of the intervention on the mispricing—stemming from the increase in the three frictions of liquidity, repo cost, and repo uncertainty, resulting from the scarcity of bonds available to the market. We assess the importance of the direct and indirect channels in the next section. Figure 3 shows that this first approximation of the mispricing, especially for the Italian futures contract, is generally near zero, before the QE period, as one would expect if the market was almost frictionless.

Insert Figure 3 here.

The three-month periodicity that is observed in Figure 3 stems from the definition of the futures contract: the futures contract has to be worth exactly the same at delivery, where no borrowing of the bond would even be needed, thanks to the pull-to-parity effect. On the tenth day (or the next business day if this is a holiday) of March, June, September, and December (i.e., at delivery), the basis is null, and the time series we draw approaches the x-axis. Figure 1 shows a rescaled and censored version of the $Basis_t$ from Figure 3. That is, for ease of exposition, we remove the deterministic periodicity of the basis by scaling $Basis_t$ by the number of days to delivery, and censor the basis to be non-negative, to focus on bond overpricing. That is, we plot $\frac{\sum_{m=1}^{380} \max(Basis_{m,t}, 0)}{100 \cdot 380} \frac{365}{\text{Days to Delivery}}$ in Figure 1. This scaled measure still approaches zero as delivery becomes imminent, but is otherwise an almost continuous line. While this alternative measure has an intuitive interpretation (setting the duration of the arbitrage tenor to exactly one year) and would be useful for someone trading the basis, we prefer to concentrate our analysis on $Basis_t$, as it directly translates into a mispricing in euros and is directly comparable across trading days and countries.

For a preliminary look at the mispricing, we report the average daily $Basis_t$ in Panel A of Table I, in cents of euros per €100 of face value, for the January 2013–February 2015 and the March 2015–April 2017 periods (i.e., before and during the QE intervention). We also report the difference between the average basis in the two periods and the statistical significance of its difference from zero. The effect that the ECB bond purchases had on the basis was statistically significant: before the QE intervention, the mispricing was less than a euro cent, on average. During the QE intervention, however, bonds were substantially more expensive than their futures counterpart, as the basis averages €7 cents, with the difference being significant at the 1% level. In yield terms, which are commonly used in bond pricing, a €7 cents basis correspond to a 0.7bp difference between the bond yields and the futures-implied yield.[19] To test and quantify the effects

[19]We can approximate the duration of the bond to ten years and use the price-to-yield changes formula: $\frac{\Delta P}{Duration} \sim$

ECB bond purchases had on the futures-bond basis, we investigate the direct and indirect economic channels in Section VI.

Insert Table I here.

To further illustrate the dislocation in the bond-futures pricing relationship, we calculate how long it takes for half of a €1 shock to one of the prices to be reflected in the price of the other asset. That is, we calculate the half-life, $HalfLife_{it} = \frac{\log(0.5)}{\log(1+\alpha)}$, of a unit-sized shock to one of the prices, based on the parameter of an auto-regressive system, $\Delta Basis_{it} = \alpha Basis_{t-1} + \epsilon_{it}$. This specification corresponds to a co-integrated system of futures and bond prices, where the co-integrating vector is $(1, -1)$ and no deterministic trend is present in the prices of the assets. We estimate this specification for every hour of trading in our sample and obtain a daily half-life estimate series from the median α for country i and day t. We plot the series in Figure 4.

Insert Figure 4 here.

Figure 4 offers an alternative interpretation for the dislocation shown in Figure 3 and Table I: Before the QE, a €1 shock to the futures price would be reflected in the bond price, on average, within 20 (100) minutes for the Italian (German) market. During the ECB intervention, on the other hand, it took about three times as long for the same shock to be absorbed (i.e., 73 (273) minutes). Underlying this estimation is the restriction that neither the co-integration vector nor the equation for the change in prices contain a constant. While we argue that the data do not support this hypothesis, showing that $Basis_{it}$ is significantly different from zero and time varying, the co-integration analysis provides an alternative representation of our results.

VI The Direct and Indirect Effects of the ECB Intervention on the Futures-Bond Basis

In this section, we investigate and quantify the channels through which the bond purchases by the central bank affected the divergence between the price of the sovereign bond futures contract and that of the underlying cash bond, which is shown in Figure 3. To do so, we analyze the direct effect

$\frac{0.07}{10} = 0.7$bp.

that the ECB had on the mispricing through the increase in bond prices and the indirect effects it had through its impact on the frictions it sought to leave unaffected, according to the guidelines laid out by Cœuré (2015) and reported in Section I.

The ECB, like other central banks engaged in QE efforts, "wants to affect prices": the ECB purchases and holds on to a steady flow of bonds, acquiring them from market participants whose reserve prices are increasing in the quantity purchased, given the near fixed-supply nature of the assets. The consequent increase is the *direct* effect of the ECB's QE, through scarcity and price pressure, on the relative pricing of the bonds being purchased. In a frictionless market, this direct effect would be the sole channel for the impact of ECB purchases on bond prices. In a world with unlimited capital available at the risk-free rate and with no transaction costs, such a direct effect could result in an arbitrage opportunity that traders would take advantage of immediately, and would then necessarily be of only a temporary nature, in the tâtonnement toward a new equilibrium.

In the more realistic setting of a world with market frictions, however, impediments to the law of one price can exist, so that the prices of cash bonds and futures may diverge, implying a mispricing, even in the absence of actual arbitrage opportunities. The presence of a large bond bid-ask spread, for example, means that midquotes for the bond and futures contract can be significantly different. The improvement or worsening of these frictions represent the *indirect* effect of the ECB's QE on the futures-bond mispricing.

In order to disentangle these multiple effects, we proceed as follows: first, we identify the frictions that contribute to the mispricing and show how the scarcity following the QE affected them (i.e., the QE's indirect effects), and then proceed to quantify the intervention's direct effect. The frictions that we identify as the indirect channels through which ECB intervention creates the mipricing between bond and futures are "liquidity and collateral availability" (Cœuré, 2015). In Subsection VI.A, we analyze the liquidity of the bond market: as the ECB employs a buy-and-hold strategy, fewer bonds are available for purchases to traders, and the turnover of the bonds decreases, increasing the market makers' inventory risk and decreasing their willingness to offer liquidity in the cash bond market. In Subsections VI.B and VI.C, we study the cost and availability of obtaining bonds via repo transactions: As the central banks hold on to a larger fraction of available bonds, institutions with a need for highly liquid collateral securities become willing to pay more to acquire them, decreasing the corresponding repo rate and contributing to the bonds' shortage.[20] Finally,

[20]Both the ECB and national central banks of the member states of the Euro-zone implemented facilities for lending the securities they purchased over time. The ECB's security lending facility was established on April 2, 2015, i.e.,

in Subsection VI.D, we quantify the direct effect of the ECB's purchases on the mispricing and quantify the contribution of each channel to the mispricing in Figure 3.

VI.A The Indirect Effects of ECB Intervention: The Bond Market Liquidity

The question as to the overall effect of the outright purchases of bonds by a central bank on their market liquidity is ultimately an empirical one.[21] On the one hand, the outright purchases could make market makers more willing to take on inventory risk and purchase bonds from their customers, thus providing liquidity, since they know they will be able to lower their inventory risk, almost at will, by selling them to the central bank. On the other hand, market makers' willingness to hold inventory and market liquidity for bonds could be adversely affected by the scarcity resulting from ECB's purchases: larger central bank bond holdings mean a smaller float and a reduced dispersion in ownership. If the schedule of purchases by the central bank is not known with some certainty at the individual bond-level, market makers may be concerned that a given bond will no longer be targeted by the intervention in the future and that, if they agree to purchase it from a client, they might have to hold it in their inventory for a longer period. A risk-averse market maker would, therefore, only buy the bond at a discount, worsening the liquidity they offer to their customers.

The effect the intervention has on market liquidity is clearly important to assess the relative pricing of the cash bonds with respect to the futures contract: if we consider the ability of a trader to replicate a short future position, for example, by selling a bond as a component of price discovery, an increased bond bid-ask spread would prevent her from successfully conducting the replicating strategy. Similarly, because the price at which the bond can be sold (i.e., the bid price) is further away from the bond midquote, due to a decline in liquidity, the likelihood that a profitable arbitrage opportunity arises—assuming that the arbitrageur is forced to pay the full bid-offer spreads in the cash bond and futures market—decreases. In terms of the mispricing and failure of the price discovery process, an increased bond bid-ask spread, for example, means that the midquotes of the cash bond and the futures contract can diverge even more significantly, increasing the range of possible relative prices, leaving the market uncertain on the true price.

---

during the sample period we consider. Our findings suggest that it was not successful in curtailing the decreasing availability of securities during the QE, as Subsection VI.B shows. Starting from December 2016, central banks extended the facilities to accept cash for collateral of the lending operations. In any event, the repo rates we used in our analysis ought to have captured the impact of these structural changes.

[21] D'Amico and King (2013), Pelizzon et al. (2016), Pericoli and Veronese (2017), Schlepper et al. (2017) and Christensen and Gillan (2018) recently addressed this issue.

Figure 5 shows the time-series of the bid-ask spread for the CTD bond for the German and Italian futures contracts. Noticeably, the highest levels of illiquidity were reached during the QE period for both countries. While an upward trend is visible for both series, the identity of the CTD bond and, with it, the characteristics of the bond that determine its liquidity, varies through time.

Insert Figure 5 here.

To assess whether central bank purchases affected bond market liquidity, we regress the bid-ask spread of the CTD bond for country i on day t, BA^B_{it}, on the fraction of bonds of that country that are held at the ECB, $ECB^{\%}_{it}$, and a series of control variables:

$$\begin{aligned} BA^B_{it} = \alpha + \beta_1 ECB^{\%}_{it} + \beta_2 DE_{it} + \beta_3 TTM_{it} + \beta_4 Long_{it} + \beta_5 AmtIssue_{it} + \beta_6 \sigma^B_{it} \\ + \beta_7 Volume^B_{it} + \beta_8 CCBSS_t + \varepsilon_{it} \end{aligned} \tag{2}$$

where DE_i is a dummy variable that is one for a German asset and zero otherwise; TtM_{it} is the time to maturity of the bond, in years; $Long_i$ is a dummy variable, which is one if the bond had 15 years to maturity when it was issued (15-year bonds, which are deliverable into the Italian futures contract, are generally less liquid than their 10-year counterparts, the benchmark maturity); $AmtIssue_i$ is the amount issued, in billions; σ^B_{it} is the volatility of the bond returns; and $Volume^B_{it}$ is the bond's traded volume, in billions. Finally, we control for European market–wide funding liquidity conditions by using the value of the cross-currency basis swap spread $CCBSS_t$, a measure of dollar-denominated funding illiquidity.[22] We control for bond-specific determinants of liquidity in order to disentangle the effect of the characteristics of the CTD bond from that of the ECB holdings in determining that bond's liquidity, following the specifications in Pelizzon et al. (2016).

The sample consists of one observation for the CTD bond underlying the German and Italian futures contract, respectively, for each of the 1,058 trading days in our sample period, for a total of 2,116 observations. Standard errors are two-way clustered, at the bond and date level. We report the results in Table II.

[22]Pelizzon et al. (2016) shows that, after 2012, funding liquidity measured by the $CCBSS_t$ is a good predictor of bond market liquidity. This spread represents the additional premium paid per period for a cross-currency swap between Euro Interbank Offered Rate (Euribor) and US dollar London Interbank Offered Rate (LIBOR). Market participants view it as a measure of the macro-liquidity imbalances in currency flows between the euro and the US dollar, the global reserve currency. In a frictionless market, the CCBSS should be near zero. In fact, it has been consistently different from zero since the Great Recession. Omitting this variable would result in attributing the effect that funding liquidity had on market liquidity to the ECB intervention.

Insert Table II here.

In Specification 1 of Table II, we show that, controlling for the nationality of the bonds, a 10% increase in the bond holding by the ECB, which the central bank reached after one year of QE, increased the bid-ask spread by €1.9 cents, corresponding to a 30% increase over the before-QE average bid-ask spread of €6.4 cents, which is highly significant, both economically and statistically. Thus, by increasing the bid-ask spread on the cash bond market by virtue of its massive purchases of cash bonds, the ECB impeded the process of price discovery. In other words, based on our interpretation of Cœuré (2015), our contention is that the ECB allowed the mid-price of the CTD bond to diverge from its futures contract counterpart by increasing the range within which the quotes could differ (i.e., the bid-ask spread) before arbitrage forces could intervene to facilitate their convergence.

Including bond-specific determinants of market liquidity, as we do in Specifications 2 and 3, or a market-wide measure of funding liquidity, as we do in Specification 4, does not significantly alter our conclusions, indicating that the trend we observe in market liquidity is not driven by the changing identity of the CTD bond or the evolution of market-wide liquidity drivers.[23] In Specification 5, we replace the left-hand-side variable with its log-transformation, which allows us to express the results as an elasticity: A 10% increase in ECB holding increased the bid-ask spread, on average, by 21%, consistent with the previous specification.[24]

Without detailed data on exactly which bonds were purchased and when, it is impossible to disentangle the direct effect the ECB had on the liquidity of CTD bonds from the indirect effect it had through the purchases of their close substitutes.[25] In Specification 6, we replicate the regression in Specification 1, using the average bid-ask spread of *all* deliverable bonds that are not the CTD as the dependent variable. The results are very similar to those in the original specification, indicating that the effects the ECB purchases had on the CTD bond are not dissimilar to the effect they had on its closest substitutes.[26] However, as shown in Specification 7, the ECB purchases had a more

[23]To the extent that the ECB intervention affects repo rates, as we show in Subsection VI.B, and that repo rates may affect bond market liquidity, as in Huh and Infante's (2018), the parameter we estimate for $ECB_{it}^{\%}$ in Equation 2 captures the total effect of the bond purchases on the bond market liquidity, i.e., both the direct effect of scarcity and an indirect effect through the worsening of the market conditions on the repo market.

[24]We measure market liquidity by the quoted bid-ask spread. Other measures of liquidity, such as the quoted quantity or the effective bid-ask spread, are highly correlated with the quoted bid-ask spread (see Pelizzon, Subrahmanyam, Tomio, and Uno 2013).

[25]D'Amico and King (2013) perform such analysis, by considering the indirect effect FED purchases had on the yield of a given bond via the purchase of its close substitutes.

[26]Data provided by Trax show a figure consistent with our finding, i.e., that the overall bond market liquidity

deleterious effect on the CTD bond than on the average deliverable bond, but the differential impact is only marginally significant, statistically and economically.

VI.B The Indirect Effects of ECB Intervention: The Repo Rate

A second channel through which the central bank can affect the futures-cash bond relative pricing is through the gain/cost incurred by the trader who replicates a short futures position by borrowing the bond on the repo market to sell it short. That is, a second reason why the basis in Equation (1) is not an accurate representation of an arbitrageur's profits is that we may have overestimated the repo rate by using an unsecured "riskless" rate, the overnight EONIA, as a proxy for the "special" repo rate the arbitrageur could actually obtain on the market on a secured basis, hence overestimating (underestimating) the arbitrageur's profits (losses) from lending money against the CTD bond. Figure 6 shows the overnight EONIA rate, the RFR for Germany and Italy (dashed)—a quantity-weighted repo rate index calculated with transactions, both GC and special, involving sovereign government bonds, and taking place on the MTS and BrokerTec platforms, and published by the NEX Group—and the special repo rates for the specific CTD bonds.[27] The daily measure of special repo rates for the CTD bonds, $CTDRepo_{it}$, is calculated as the median special repo rate from all transactions taking place on the MTS platform for the CTD bond of country i on day t.[28]

Insert Figure 6 here.

Figure 6 shows that the unsecured lending rate is indeed not a fair representation of the interest payment the arbitrageur would obtain when lending money in exchange for the bond that she would

declined in the sample period we consider, and that the trade count across the European bond market was its lowest in the third quarter of 2017, at €1.66 million, since at least the first quarter of 2015, when it was 2.3 million (https://www.fi-desk.com/europes-government-bond-market-hits-electronic-ceiling/).

[27]Repo transactions based on Italian bonds take place mostly on the MTS platform, while transactions based on German bonds occure most often on BrokerTec (see Mancini, Ranaldo, and Wrampelmeyer (2015) for an extensive exposition of the European repo market). We replicate the RFR indexes for the two countries using the same data selection and aggregating procedures detailed by NEX Group—using rates for both GC and special repo transactions and weighting them by traded amount—but only using the transactions taking place on the MTS platform. We find a correlation between the replicated RFR indexes based only on MTS transactions and the original indexes of 96% and 97% for Germany and Italy, respectively, indicating that the sample of repo transactions we observe is representative of the whole repo market.

[28]We restrict the trades we consider in order to calculate the median special repo rate to transactions with a tomorrow-next, spot-next, or overnight term. That is, we consider only one-day transactions, which make up 98.6% of all special repo transactions in the MTS sample. RFRs are quantity-weighted averages of GC and special transactions that satisfy similar requirements. When no observations are available for a given date for the CTD bond, which only happens for the sample of German CTD bonds, we consider the latest available observation.

eventually sell, as part of the arbitrage transaction. While the repo rate indexes are fairly close to the unsecured rate in the first half of the sample, starting in 2015, the RFR diverged substantially from the unsecured EONIA rate. The EONIA rate, on the other hand, flattens out just above the deposit facility rate at the ECB (-40bp after March 2015). The divergence between the EONIA and the repo rates, which is especially marked for the German market, stems from the bond scarcity following the ECB purchases: as more and more bonds were held at the central bank, institutions looking for collateral were forced to obtain it on the repo market via a reverse repo, for which they are willing to give up part of the interest gain (ending up even actually paying to lend out money/borrow the security, toward the end of the sample). Figure 6 also shows that the CTD bonds trade at a premium even higher than other bonds, as indicated by their repo rate being even lower than the RFR (the CTD bond is often the on-the-run benchmark bond, which, together with its use in basis trades, could explain its extreme specialness). The RFR, however, includes both GC and special transactions, biasing it away from the pure CTD special rate. We calculate what the RFR would have been if only special transactions, and not GC trades, were considered and call this special-only index $\widehat{RFR}$. While the resulting index is considerably lower than the RFR, due to the exclusion of GC transactions, it is still higher than the repo rate commanded by the CTD bond.

We test the relationship between the repo rates prevailing on the market for the CTD bonds and the proportion of bonds held by the ECB, regressing different repo rate measures on the fraction of bonds held at the ECB, $ECB^{\%}_{it}$, and other covariates. More formally, we estimate:

$$CTDRepo_{it} = \alpha + \beta_1 ECB^{\%}_{it} + \beta_2 DE_{it} + \beta_3 \sigma^B_{it} + \beta_4 AmtIssue_{it} + \beta_5 BA^B_{it} + \beta_6 TtM_{it} + \beta_7 Long_{it} + \varepsilon_{it} \quad (3)$$

Insert Table III here.

and report the results in Table III. Specification 1 shows that a 1% increase in the holding of sovereign bonds at the ECB decreased the interest rate earned from lending money against the CTD bond by 6.76bp. The bond collateral scarcity resulting from the ECB's QE purchases decreased the repo rate (i.e., decreased the gains for a trader trying to replicate a short futures position with the short sale of a bond). In Specification 2 (3), we regress the RFR ($\widehat{RFR}$) and show that bond scarcity negatively affected the repo rates for all German and Italian bonds, and not only for the CTD bond.

In Specification 4 (5) of Table III, we regress the difference between the CTD bond repo rate and the RFR ($\widehat{RFR}$) on the percentage of bonds held at the ECB, and bond-specific characteristics that could explain the bonds' specialness: the CTD bond is, in fact, more special than other bonds in the sample, and its incremental specialness is not explained by its volatility or level of liquidity.[29]

VI.C The Indirect Effects of ECB Intervention: The Uncertainty in the Repo Rate

The naïve mispricing in Equation (1), while technically correct, assumes the existence of a term repo market (i.e., a market wherein the arbitrageur can borrow the deliverable bond from day t to delivery day T). However, term repo transactions are exceedingly rare: in our sample, 98.6% of all special repo transactions on the MTS platform had a term of one day. To effectively replicate a short position (i.e., to ensure a smooth price discovery process), a trader would have to roll over her repo position on a daily basis, thus exposing herself to the risk that the repo rate could move against the position over the life of the trade.[30] Similarly, an arbitrageur rolling over her short bond position would be exposed to the rollover risk (i.e., the risk that the repo rates may move up or down each day until the maturity of the futures contract, when the transaction will be fully unwound).[31] Hence, while we show in Subsection VI.B that ECB purchases affected the *level* of the repo rates, the scarcity they created affected the availability of the CTD bonds on the repo market, and thus the uncertainty of the repo rate as measured by its *dispersion*.

Insert Figure 7 here.

To investigate this third channel through which the QE can affect the cash bond-futures mispricing (and the profitability of arbitrage trades), we calculate the dispersion of the repo rate of the

[29]The repo rates series may appear non-stationary in Figure 6. However, the trend in the series looks very similar to the (opposite of) the trend in ECB bond holdings. Accordingly, we verify the non-stationarity of the residuals of Specification 1 with an Augmented Dickey Fuller test with two lags, and we cannot reject, at the 1% confidence level, the alternative hypothesis of an absence of a unit-root in the series for either country. In other words, the trends in Figure 6 are of a deterministic nature, around ECB holdings, and not of a stochastic nature.

[30]This is analogous to the effect of convexity in the swap futures-spread analyzed in Gupta and Subrahmanyam (2000).

[31]The absence of a heavily traded term repo market may raise the question of whether the trade we outline is, in fact, an arbitrage. We are sympathetic to the argument that, if the term repo market did not exist, the trade would not qualify as an arbitrage. Nonetheless, however sparce, we do observe term repo transactions, particularly during the second half of our sample. The term repo trades take place, on average, at rates that are 1bp higher than overnight transactions for the same bonds on the same day, pointing to an upward sloping term structure of repo rates. Accounting for such upward slope in the basis calculation would deliver an even larger mispricing than what we report in our paper. The presence or absence of a term repo market, however, is immaterial to our consideration on the cost-effectiveness of the ECB's QE.

CTD bond, as its interquartile spread, $RepoRange_{it}$—that is, the difference between the 75th and the 25th percentile of the distribution of the CTD bond special repo rate. We plot the time series of this variable in Figure 7. We regress $RepoRange_{it}$ on the amount of bonds held at the ECB and bond-specific variables and report the results in Table IV:

$$\begin{aligned} CTDRepoRange_{it} = \alpha + \beta_1 ECB^{\%}_{it} + \beta_2 DE_{it} + \beta_3 \sigma^B_{it} + \beta_4 AmtIssue_{it} + \beta_5 BA^B_{it} \\ + \beta_6 TtM_{it} + \beta_7 Long_{it} + \varepsilon_{it} \end{aligned} \tag{4}$$

Insert Table IV here.

Specification 1 in Table IV shows that a 1% increase in the quantity of bonds held at the central bank increased the dispersion in the repo rates by 67.8bp, over a pre-QE average of 2.6%. The increased uncertainty in the repo rate resulting from the CTD bond's scarcity hinders the price discovery process, since the rollover risk in the repo rate would drive a wedge between the risk profiles of shorting the futures contract versus shorting the bond. Alternatively, an arbitrageur facing a higher rollover risk on the short leg of her transaction would require the mispricing to be larger before entering a basis transaction, as compensation for the higher risk she bears. We select $RepoRange_{it}$ as a measure of rollover risk because of its robustness to outliers. However, similar results are obtained when we use the standard deviation of the repo rates for the transactions of CTD Bond–i on day-t, $CTDRepo\sigma_{it}$, as a left-hand-side variable, which we do in Specification 3.

VI.D The Direct Effect of ECB Intervention

On top of the indirect effects we documented in Subsections VI.A, VI.B, and VI.C, the ECB intervention could have affected the mispricing between bonds and futures directly, by means of exerting a large buying pressure on the bond prices. We can interpret the combined magnitude of the indirect channels and the direct one as the *total* effect of the QE on the futures-bond mispricing.

We first quantify the total effect of the ECB bond purchases in Specification 1 of Table V, where we report the results of regressing the mispricing variable $Basis_{it}$ on the fraction of bonds held at the ECB, $ECB^{\%}_{it}$, the days-to-delivery variable DtD_{it}, and a country dummy DE_i:

$$Basis_{it} = \alpha + \beta_1 ECB^{\%}_{it} + \beta_2 DE_{it} + \beta_3 DtD_{it} + \varepsilon_{it} \tag{5}$$

Insert Table V here.

Specification 1 of Table V shows that a 1% increase in bond holdings increased the mispricing between bonds and futures by €0.8 cents.[32] This parameter represent the *total* effect that the bond purchases by the central bank and the resulting bond scarcity had on the mispricing, conflating the QE's direct and indirect effects.

To gauge the magnitude of the *direct* effect of the bond purchases, we repeat the analysis in Specification 2, controlling for the indirect effects detailed in subsections VI.A, VI.B, and VI.C:

$$\begin{aligned} Basis_{it} &= \alpha + \beta_1 ECB^{\%}_{it} + \beta_2 DE_{it} + \beta_3 DtD_{it} + \beta_4 BA^{B}_{it} + \beta_5 CTDRepo_{it} \\ &\quad + \beta_6 CTDRepoRange_{it} + \varepsilon_{it} \end{aligned} \tag{6}$$

The estimate of the direct effect of the purchases, once the indirect effects through the frictions are controlled for, is statistically significant and sizeable: a 1% increase in bond holdings increased the mispricing between cash bonds and futures by €0.3 cents, giving us an overall estimate of €7.6% · 0.3 = 2.3 cent, for the average level of ECB holdings in our sample period. The regression results indicate that $\frac{0.283}{0.817} = 35\%$ of the mispricing stems from the *direct* effect of the intervention by driving a wedge between the prices of the cash bond and the futures contract, while the remaining two-thirds are a result of the indirect effect, through market liquidity and repo rates effects. Alternatively, we could estimate the direct effect by changing the dependent variable to take directly accounting for the trading and funding costs, rather than including them as regressors, which we do in the next section.

We can estimate the significance of the indirect effects by multiplying the parameters for each of the three variables in Specification 2 of Table V—BA^{B}_{it}, $CTDRepo_{it}$, and $CTDRepoRange_{it}$—by the parameters for $ECB^{\%}_{it}$ in Tables II, III, and IV. The bond liquidity channel, therefore, contributed to $\frac{0.189 \cdot 0.169}{0.871} = 4\%$, the repo rate channel accounted for $\frac{(-6.759)\cdot(-0.074)}{0.871} = 57\%$, and the repo rate uncertainty channel contributed to $\frac{0.678 \cdot 0.048}{0.871} = 4\%$ of the total effect of the ECB's QE on the mispricing.

Rather than conducting our analysis in levels, we can alternatively analyze the changes in the mispricing variables. In Table VI, we repeat the analysis in Table V, employing contract-by-contract changes in the variables. That is, we create differenced versions of the variables by subtracting, from the level of the variable on, for example, the 20th day-to-delivery of the September 2016

[32] On average, in our sample, the ECB held 7.6% of bonds during the QE, which translates into €6.2 cents of mispricing between futures and cash bonds, similar to the univariate figure shown in Table I.

contract, the level of the variable on the 20th day-to-delivery of the previous contract, the June 2016 contract. We add the prefix Δ_{90} to the variables to symbolize that we subtract from the day-t realization the value of the variable about 90 days prior (i.e., $\Delta_{90}Basis_{i,t} = Basis_{i,t} - Basis_{i,t-90}$), so that we can express the counterpart to the specification in Equation (6) as:

$$\Delta_{90}Basis_{it} = \alpha + \beta_1 ECB_{it} + \beta_2 DE_{it} + \beta_3 \Delta_{90} BA^B_{it} + \beta_4 \Delta_{90} CTDRepo_{it} + \beta_5 \Delta_{90} CTDRepoRange_{it} + \varepsilon_{it} \quad (7)$$

This approach allows us to sidestep the pull-to-delivery effect that would complicate the analysis of the first-differenced variables using calendar dates, and to focus on the contribution of the ECB intervention to the basis. To reflect the imposed negative correlation between $\Delta_{90}Basis_{i,t}$ and $\Delta_{90}Basis_{i,t-90}$, as they share an observation, we cluster the standard errors by day-to-delivery and day. The variable of interest is ECB_{it}, which equals one if the ECB's QE is in force and zero otherwise. Its statistical significance is high and comparable to that of $ECB^{\%}_{it}$ in Table V, indicating that our findings are robust to varying the statistical setup.

Insert Table VI here.

VII Arbitrage Opportunities between Bonds and Futures

The mispricing we derived in Section V and presented in Figure 3 does not correspond to foregone arbitrage profits, since the liquidity and funding costs are not properly accounted for. For example, on January 6, 2016, the mispricing measure $Basis_{it}$ for Germany was €0.09, while the arbitrage profit was zero, as transaction and repo costs sum up to more than €9 cents, rendering the trade unprofitable. In this section, we argue that actual *tradable* arbitrage opportunities actually arose, as a direct consequence of the ECB's bond purchases. We calculate the foregone arbitrage profits or losses using Equation (1), where we substitute the bond price B_{mt} with the bond bid-quote, since the arbitrageur would sell the bond to the ECB, the futures price $F_{m,t}$ with the futures contract's ask-quote, to include the trading costs borne by the arbitrageur, and employ the median special repo rate we analyzed in Subsection VI.B, instead of EONIA, for r_t, to include the funding costs of the bond leg of the arbitrage trade. The resulting tradable basis $TradeBasis_{it}$ is shown in Panel A of

Figure 8.[33] As the arbitrageur would only enter a basis trade if the resulting profit were positive, we more accurately portray foregone arbitrage profits as the daily average of the minimum between the observations of $TradeBasis_{it}$ at a minute frequency and zero, $Arbitrage_{it} = \frac{\sum_{m=1}^{380} \max(TradeBasis_{m,t},0)}{380}$, which we show in Panel B of Figure 8.

Insert Figure 8 here.

$TradeBasis_{it}$ of Figure 8 is significantly lower than $Basis_{it}$ of Figure 3, due to accounting for the trading frictions; yet, the two time series show a similar pattern, with larger deviations up to €28 cents occurring during the implementation of the QE. $TradeBasis_{it}$ is often significantly below zero, indicating that an arbitrageur would have incurred losses if she were to trade. $Arbitrage_{it}$ in Panel B—the foregone arbitrage profits—indicates that arbitrage opportunities did arise as the bond scarcity increased, following the ECB's cash bond purchases. For Italy, in particular, 92% of the observations with positive $Arbitrage_{it}$ in our sample took place during the ECB's QE.

To quantify the effect of QE on $TradeBasis_{it}$ and $Arbitrage_{it}$, we report a univariate test that $TradeBasis_{it}$ ($Arbitrage_{it}$) is the same before and during QE, in Panel B (C) of Table I. Panel B of Table I shows that, even after taking frictions into account, the average mispricing is €1.5 cents higher during the QE period and the arbitrage opportunities are €0.8 cents higher, and that both differences are highly statistically significant. We regress $TradeBasis_{it}$ on the amount of bonds held at the ECB, in Specification 3 of Table V:

$$TradeBasis_{it} = \alpha + \beta_1 ECB_{it}^{\%} + \beta_2 DE_{it} + \beta_3 DtD_{it} + \varepsilon_{it} \tag{8}$$

The results show that a 10% increase in bonds held at the central bank increased the ex-frictions mispricing by €1.8 cents. This quantity is consistent with the univariate analysis, since the ECB held, on average, 7.6% of outstanding bonds during the intervention, which would translate, according to the regression parameters, into €1.43 cents of higher mispricing, after frictions have been taken into consideration, similar to the €1.5 cents difference from the univariate analysis. We regress $Arbitrage_{it}$ on $ECB_{it}^{\%}$ in a Tobit setting in Specification 4 of Table V, which shows that the fraction of bonds held at the central bank, $ECB_{it}^{\%}$, is statistically significant at the 1% level in

[33]This calculation is conservative since it assumes that the arbitrageur would always need to pay the bid-ask spread in both legs of the transaction and that the bond trade happens on the MTS interdealer market platform. It may well be that, at least on occasion, the arbitrageur has the opportunity to capture part of the spread or trade on more favorable terms in the dealer-to-customer market, or over the counter.

explaining the probability of seeing untapped arbitrage opportunities and their magnitude.[34] We repeat the analyses using contract-by-contract differenced variables rather than their levels, as we did in the previous section, and report the results in Table VI. The statistical significance of the results remains unchanged.

While the mispricing implied by $Basis_{it}$, shown in Figure 3, signifies that the price discovery process was significantly perturbed by the QE, identifying significant and persistent arbitrage opportunities, net of liquidity and funding costs, as measured by $Arbitrage_{it}$, means that the law of one price was *de facto* suspended, albeit for a short period. In Section VIII, we advance a hypothesis for why arbitrageurs did not fully take advantage of the tradable arbitrage opportunities shown in this section.

VIII Discussion

VIII.A Regulatory Frictions

The persistence of profitable arbitrage opportunities, after accounting for all relevant frictions (i.e., the "money left on the table") shown in Subsection VI.D raises the question of why arbitrageurs did not, in fact, take advantage of them. Since we have included all relevant costs and assumed conservatively that the trader had no prior holdings and funded her futures purchase through the bond borrowing, we hypothesize that our profit calculation perhaps falls short in its implicit comparison with a required benchmark return of zero: since the trade is a perfect arbitrage, we argue, market participants will initiate it as long as the (certain) return they lock in is positive, in line with standard theory. However, our conversations with market participants suggests that this premise ignores the possibility that regulatory requirements for the deployment of capital by the principal players in these markets—financial institutions such as banks—may, however, impose a higher lower bound on the benchmark return.[35]

The various sources of regulatory costs are internal value-at-risk limits, as well as capital requirements under the Basel requirements, mainly regarding compliance with, among others,

[34]The larger parameter for $ECB^{\%}_{it}$ in Specification 4 compared to Specification 3 can be attributed to its capturing both the size of the realization of $Arbitrage_{it}$ and the probability of a non-censored observation (i.e., a profitable arbitrage opportunity). The corresponding parameter in a standard OLS regression is 0.136, comparable to the 0.188 in Specification 3 and in line with the univariate results in Table I.

[35]Other large financial institutions such as insurance companies and asset management firms have other regulatory restrictions that are similarly binding.

leverage, net stable funding, and liquidity ratios. We can summarize the relations between the quantities of interest, in simple terms, as follows:

$$\text{Basis} = \text{Forward Bond Price} - \text{Futures Equivalent Price}$$
$$\text{Tradable Basis} = \text{Basis} - \text{Market Frictions} \geq \text{Regulatory Costs}$$
$$\text{Market Frictions} = \text{Trading Costs} + \text{Repo Costs}$$

An indicative example of how these requirements might affect an arbitrageur's trading considerations can be easily sketched out by considering how compliance with Basel-mandated leverage ratio constraints affects the required return of the trade.[36] Basel III introduced a non-risk-based leverage ratio, obtained by dividing Tier 1 capital by the bank's average total consolidated assets (including also the notion of the bank's derivative positions), which banks must keep above 3%, or 5%, if they are systemically important.[37] To see how this requirement affects a basis trade, consider a bank that has a required return on capital of 10%. In order for the bank to consider a futures-bond arbitrage profitable, it has to yield an annualized return of 10% on the capital that is employed for the trade. At the margin, the arbitrage trade should, thus, return 10% on the 5% of capital it employs—i.e., it should have an annual return of $10\% \cdot 5\% = 50bps$. Such regulatory considerations, therefore, raise the annual required return, even on a riskless arbitrage trade, from zero to 50bps.[38]

To gain some intuition regarding how such a minimum required return may explain the existence of a positive tradable basis, let us assume that an arbitrageur enters the trade on the very first trading day of a new contract, repeating the trade (thus employing the same capital) four times

[36] For a general discussion of the role of leverage constraints on the required return of a trade, see Andersen, Duffie, and Song (2018).

[37] AFME (2012) provides a list of the market makers who are members of the MTS platform. A list of global systemically important financial institutions can be found on the website of the Financial Stability Board, `http://www.fsb.org/`. BIS (2014) provides details on the computations of the leverage ratio.

[38] This begs the question of why such a high risk-adjusted cost of capital should be applied to what is, in fact, a near-riskless trade. Numerous conversations with bank personnel and regulators have convinced us that this type of calculation—not the precise numbers—is widely employed, since risk managers set overall risk limits at the desk level for a variety of trades, some of which are risky, while others are almost riskless. In turn, trading systems and the traders who use them use the value-at-risk calculations *across the board* for individual transactions, without parsing the riskiness on a trade-by-trade basis. Cenedese, Della Corte, and Wang (2018) show that leverage ratio–implied costs keep the covered interest rate parity from holding. More specifically, Fleckenstein and Longstaff (2018) quantify that on average, "balance sheet constraints add 81 basis points to intermediary funding costs", and that this estimate is larger during periods of crisis.

during the year, corresponding to the four quarterly deliveries, in March, June, September, and December. In order for the trade to deliver a return higher than 50bps, the basis needs to be at least €$\frac{50bps}{4}100 = 0.125$ before the trade is profitable, in a capital-adjusted sense. Panel B of Figure 8 shows that the tradable basis exceeded €0.125 on only a handful of days in our sample, and solely for the German sample.

The presence of regulatory requirements can explain why we observe arbitrage opportunities (as in Du et al., 2018) and speaks to the feasibility of a market-neutral central bank intervention. Capital requirements, such as the leverage ratio detailed in the Basel III regulation, were present both prior to and during the interventions; yet, we observe tradable arbitrage opportunities and sizable mispricing only when the ECB's QE purchases were pushing bond prices away from their futures counterparts. We interpret this finding as suggesting that, in the absence of dislocating trades by the central bank, regulatory requirements do not impede arbitrage activity, and markets function effectively. When the price discovery mechanism is perturbed, however, arbitrage forces are kept from aligning the asset prices on account of banks' capital regulation. In sum, the twin effects of central bank intervention in the cash bond market and the blunting of the arbitrage mechanism due to the imposition of bank regulatory capital requirements creates the possibility of a tradable basis. The mispricing we document is, thus, the result of two contemporaneous forces: the buying pressure and market dislocations following the ECB's bond purchases, and the regulatory capital constraint implying non-negative minimum required returns on riskless trades, because of the regulatory capital they employ. We expect that, if no capital constraints were imposed on financial institutions, arbitrageurs would eliminate any temporary mispricing resulting from the central bank's actions; conversely, without any central bank intervention, no major disruption would lead to a systematic failure of the price discovery process in the markets.[39]

While we carefully lay out the channels that link the asset purchases by the ECB to the mispricing we observe on the market, it may be that there are other causes that drive the relative pricing of futures vis-a-vis bonds which are unrelated to the ECB intervention. To make this argument convincingly, however, we would need to find out a driver of the mispricing which is relevant after March 2015, but not before March 2015. The monthly ECB purchase data correlate at the 63% level with the mispricing we calculate. While correlation does not mean causation, we are hard pressed

[39]One may well ask why an unregulated entity such as a hedge fund does not take advantage of the profitable arbitrage; the answer is that the counterparty in the cash bond borrowing/repo transactions is likely to be one of the major banks, the market makers, who would again be bound by the same regulatory frictions.

to find a convincing alternative story to the one we lay out. We can safely rule out reverse causality concerns, as the ECB does not decide how much to buy based on the mispricing we observe and the amounts of bonds bought are constant through time, with well-anticipated jumps, almost to the extent of appearing deterministic. An alternative empirical occurrence that could explain the high correlation would have to be based on finding a variable that drives both ECB purchases and the mispricing over time. Again, ECB purchases are fairly constant through time and no stochastic variable can explain such a deterministic trend. It is possible, surely, that it so happens that the ECB purchased more and more bonds, and that some underlying omitted variable that grows at the same pace of the ECB holdings exists and drives our results, but is not driven by ECB purchases. We are hard pressed to find a plausible variable that would fit this profile of a driver that is irrelevant up to March 2015 and picks up at the same pace as the ECB purchases from March 2015 and onwards and that is not driven by the ECB purchases.

VIII.B Quantifying the Trasfer to Financial Institutions

Quantifying the welfare impact of central bank interventions is an economist's Gordian knot, given the far-reaching implications for the various agents' portfolio allocation and consumption decisions. Establishing whether the mispricing we observe is a symptom of a deadweight loss is beyond the scope of our paper. However, we can address the transfer that took place from the central bank (i.e., the tax payers) to financial institutions, and to the cost-effectiveness of the intervention: The arbitrage trade we consider allows us to calculate the losses the central bank incurred as it *overpaid* for the CTD 10-year German and Italian bonds and, under some generalizing assumptions, for the universe of European sovereign bonds.[40]

If we assume that 1) the ECB either could have purchased the bonds at the midpoint (which is a conservative assumption, since central banks often obtain bonds via reverse auctions, obtaining them at competitive prices) or that the assets' midpoint prices are a good representation of their value, and that 2) the relative mispricing we observe for the CTD bonds can be generalized for all bonds targeted by the ECB, we can gauge how much the ECB overpaid for the assets by taking an appropriate multiple of the mispricing we report in Panel A of Table I.[41] A $Basis_{it}$ of €7.3 cents

[40]In contrast, Song and Zhu (2018b) show that the Federal Reserve *underpaid* for the bonds it purchased in the context of its QE.

[41]Schlepper et al. (2017) support our first assumptions, showing that 99% of German securities purchased in the context of the PSPP were acquired at prices within the best bid- and ask-quotes quoted on the MTS or at better prices

per €100 worth of bonds, considering that the ECB purchased €830 billions worth of BTPs and Bunds, translates into a loss of $\frac{830}{100} \cdot 0.073 =$ €606 millions for the two countries we consider. If a similar mispricing was common to the totality of the €2 trillions spent on European sovereign bonds in the context of the QE between March 2015 and May 2018, the corresponding figure would increase to €1.46 billions. To provide a context to these numbers, the ECB's total annual operating expenses were €1.075 billions in 2017, suggesting that the transfer we quantify is rather sizable and that the intervention could have been conducted in a more cost efficient manner, as we outline in the next subsection. In sum, the overpayment we quantify is not a direct welfare cost, but, rather, it is a mere transfer, i.e., a subsidy. The ECB could have lowered bond yields by the same amount while overpaying by less, indicating that the ECB is transacting inefficiently from the viewpoint of minimizing its costs. While we cannot quality the overpayment as a direct welfare loss, we can interpret it as a (unnecessary) transfer of wealth from tax payers to arbitageurs.[42,43]

The assumption that the mispricing we observe by measuring the relative mispricing of bonds with respect to their futures contract counterparts is constant in magnitude for all bonds purchased by the ECB is unlikely to hold in practice and impossible to verify, since futures contracts are not available for the sovereign bonds of most Euro-zone countries. While it is entirely possible that the assumption leads us to overestimate the potential social transfer to financial institutions, it is also true that the CTD bonds we consider are often the 10-year on-the-run bonds. Thus, they are in fact more liquid and more widely available than the rest of the sample, and are the bonds one would *ex ante* expect to be most precisely priced, suggesting that our estimates might actually underestimate the other bonds' mispricing. In other words, it is unclear how our findings would generalize to the other bonds of different maturities purchased by the ECB, but it would not be unlikely that their mispricing may be even larger than what we observe for the CTD, qualifying our transfer estimate as a lower bound.

The losses from impeding the price discovery process are clearly substantial, and exceed the consideration of the cost of the intervention, which we consider in this subsection. Impeding price discovery for the bond market means perturbing the price formation process of a €10 trillion

altogether.

[42] `https://www.ecb.europa.eu/pub/pdf/annrep/ecb.annualaccounts2017.en.pdf`.

[43] We can obtain a similar transfer estimate by considering the regression parameters in Table V, which yield a comparable estimate of $0.817 \cdot 7.6\% \cdot 830 =$ €515 millions for Germany and Italy, and $0.817 \cdot 7.6\% \cdot 2000 =$ €1.24 billions for the totality of the intervention, where 7.6% is the fraction of bonds held at the ECB on average over the sample period.

market, suggesting that designing truly market-neutral interventions should be an important goal for central banks going forward.

VIII.C A Market-Neutral QE

Our analysis suggests that central bank interventions cannot be market neutral, in the sense of not impeding price discovery, unless one of the following two conditions is satisfied: 1) the central bank actually pays attention to the markets connected by arbitrage (e.g., the futures and other derivatives market) and purchases those assets as well, or 2) there are no regulatory or capital constraints that prevent arbitrageurs from taking advantage of the mispricing, and that other markets, such as the repo market, continue to function properly.

While regulatory requirements serve the broader purposes of ensuring the banking system's soundness, the detailed workings of open-market interventions can be revisited. A strategy that involves purchasing both bonds and futures, for example, would alleviate concerns about "unintended consequences": purchases of both asset types decrease their respective implied bond yields, reaching the interest-rate-setting goals of QE operations, and yet bond futures purchases would have no effect on the bond scarcity of the cash market. A larger cash bond availability, in turn, would not hinder the working of the repo market and would affect the market liquidity of cash bonds to a lesser extent. A similar strategy, finally, would not subtract high-liquidity collateral from the system, thus supporting the funding liquidity of market participants. Even though the analyses in the paper focus on futures contracts, similar arguments can be made for a much broader set of derivatives, such as bond options and credit default swaps and, in general, assets correlated to sovereign bonds, such as corporate and agency bonds. While their interventions are most often conducted on the cash bonds, either via auctions or outright purchases, central banks have traded derivatives in prior instances—such as the Federal Reserve purchases of to-be-announced (TBA) mortgage-backed securities, contracts through which the regulator agreed to receive an uncertain basket of mortgages at a later date (see Song and Zhu (2018a) for details on the FED's participation in this market). The QE intervention strategy we suggest, therefore, involves tools that central banks are familiar with and would constitute a significant improvement toward "the minimisation of unintended consequences" for policy makers who "do not want to suppress the price discovery mechanism".

IX Conclusions

The QE intervention by the ECB was intended to affect the absolute, but not the relative, level of interest rates—that is, the price discovery process determining interest rates in equilibrium should not be hindered by the conduct of "market neutral" central bank operations. We demonstrate that the mispricing between cash bonds and futures caused by, and thus the welfare cost of, the ECB intervention was as high as €45 cents per €100 worth of bonds. We show that the central bank intervention affected the mispricing both directly, through the demand pressure applied to the bonds, and indirectly through the resulting bond scarcity that diminished bond market liquidity and increased the cost of obtaining the bonds on the repo market. We account for the costs that an arbitrageur would face when taking advantage of the relative mispricing (i.e., transaction, borrowing, and rollover costs), and show that the untapped arbitrage opportunities are still present in the market.

The mispricing we observe in the futures-bond arbitrage and others similar to it should concern central banks in particular, and policy makers in general, for two reasons. First, as exemplified by the speech by Cœuré, a member of the ECB's executive board, central banks value the informativeness of financial markets: the market for interest rates should be informative for monetary policy to be effective, and it is in the policy makers' interests that market participants agree on what the "correct" interest rate is. European sovereign bonds have an outstanding amount of €10 trillion, and are widely used as collateral in financial transactions in cash and derivative markets, with open interests of hundreds of billions. Second, governments and central banks are sensitive to welfare considerations: the ECB's intervention's effect of widening the gap between the prices of the two securities—and allowing traders to profit from selling the more expensive security and contemporaneously perfectly hedging by buying the cheaper security—is tantamount to a direct transfer from taxpayers to arbitrageurs (i.e., financial institutions) and needs to be examined more closely.

Our paper suggests that, in order to avoid these perverse effects, central banks should pay attention to markets connected by arbitrage (e.g., the futures and other derivatives markets) when conducting outright asset purchases. We draw policy implications from our findings and suggest that central banks achieve market neutrality in their operations by purchasing a broader set of assets, which can include cash bonds, but also futures contract and, in general, interest rate derivatives.

References

Acharya, V. V., T. Eisert, C. Eufinger, and C. W. Hirsch (2017). Whatever it takes: The real effects of unconventional monetary policy. Unpublished working paper, New York University.

AFME (2012). European primary dealers handbook. Technical Note, Association for Financial Markets in Europe.

Andersen, L., D. Duffie, and Y. Song (2018). Funding value adjustments. *Journal of Finance* (Forthcoming).

Augustin, P., M. Chernov, and D. Song (2018). Sovereign credit risk and exchange rates: Evidence from CDS quanto spreads. Unpublished working paper, National Bureau of Economic Research.

Bauer, M. D. and G. D. Rudebusch (2014). The signaling channel for Federal Reserve bond purchases. *International Journal of Central Banking 10*(3), 233–289.

BIS (2014). Basel III leverage ratio framework and disclosure requirements. Report by the Basel Committee on Banking Supervision.

Buraschi, A., M. Menguturk, and E. Sener (2014). The geography of funding markets and limits to arbitrage. *The Review of Financial Studies 28*(4), 1103–1152.

Cenedese, G., P. Della Corte, and T. Wang (2018). Currency mispricing and dealer balance sheets. Unpublished working paper, Imperial College London.

Christensen, J. H. and J. M. Gillan (2018). Does quantitative easing affect market liquidity? Unpublished working paper, Federal Reserve Bank of San Francisco.

Christensen, J. H. and G. D. Rudebusch (2012). The response of interest rates to US and UK quantitative easing. *The Economic Journal 122*(564), 384–414.

Cœuré, B. (2015). Embarking on public sector asset purchases. Speech at the Second International Conference on Sovereign Bond Markets.

Corradin, S. and A. Maddaloni (2017). The importance of being special: repo markets during the crisis. Unpublished working paper, European Central Bank.

Corradin, S. and M. Rodriguez-Moreno (2016). Violating the law of one price: the role of non-conventional monetary policy. Unpublished working paper, European Central Bank.

Crosignani, M., M. Faria-e Castro, and L. Fonseca (2017). The (unintended?) consequences of the largest liquidity injection ever. Unpublished working paper, University of Michigan.

Daetz, S. L., M. G. Subrahmanyam, D. Y. Tang, and S. Q. Wang (2017). Did ECB liquidity injections help the real economy? Unpublished working paper, Copenhagen Business School.

D'Amico, S., R. Fan, and Y. Kitsul (2015). The scarcity value of treasury collateral: Repo market effects of security-specific supply and demand factors. Unpublished working paper, Federal Reserve Bank of Chicago.

D'Amico, S. and T. B. King (2013). Flow and stock effects of large-scale treasury purchases: Evidence on the importance of local supply. *Journal of Financial Economics 108*(2), 425–448.

De Pooter, M., R. F. Martin, and S. Pruitt (2018). The liquidity effects of official bond market intervention. *Journal of Financial and Quantitative Analysis 53*(1), 243–268.

De Santis, R. A. and F. Holm-Hadulla (2017). Flow effects of central bank asset purchases on euro area sovereign bond yields: evidence from a natural experiment. Unpublished working paper, European Central Bank.

Du, W., A. Tepper, and A. Verdelhan (2018). Deviations from covered interest rate parity. *The Journal of Finance 73*(3), 915–957.

Eser, F. and B. Schwaab (2013). Assessing asset purchases within the ECB's securities markets programme. Unpublished working paper. European Central Bank.

Eser, F. and B. Schwaab (2016). Evaluating the impact of unconventional monetary policy measures: Empirical evidence from the ECB's securities markets programme. *Journal of Financial Economics 119*(1), 147 – 167.

Feldhütter, P. (2012). The same bond at different prices: identifying search frictions and selling pressures. *Review of Financial Studies 25*(4), 1155–1206.

Fleckenstein, M. and F. A. Longstaff (2018). Shadow funding costs: Measuring the cost of balance sheet constraints. Unpublished working paper, Anderson Graduate School of Management.

Gagnon, J., M. Raskin, J. Remache, and B. Sack (2011). The financial market effects of the Federal Reserve's large-scale asset purchases. *International Journal of Central Banking 7*(1), 3–43.

Ghysels, E., J. Idier, S. Manganelli, and O. Vergote (2016). A high-frequency assessment of the ECB Securities Markets Programme. *Journal of the European Economic Association 15*(1), 218–243.

Gupta, A. and M. G. Subrahmanyam (2000). An empirical examination of the convexity bias in the pricing of interest rate swaps. *Journal of Financial Economics 55*(2), 239–279.

Huh, Y. and S. Infante (2018). Bond market intermediation and the role of repo. Unpublished working paper, Federal Reserve Board.

Joyce, M., A. Lasaosa, I. Stevens, and M. Tong (2011). The financial market impact of quantitative easing in the united kingdom. *International Journal of Central Banking 7*(3), 113–161.

Krishnamurthy, A., S. Nagel, and A. Vissing-Jorgensen (2017). ECB policies involving government bond purchases: Impact and channels. *Review of Finance 22*(1), 1–44.

Krishnamurthy, A. and A. Vissing-Jorgensen (2011). The Effects of Quantitative Easing on Interest Rates: Channels and Implications for Policy. *Brookings Papers on Economic Activity 2*, 215–287.

Lando, D. and A. B. Nielsen (2018). Quanto CDS spreads. Unpublished working paper, Copenhagen Business School.

Mancini, L., A. Ranaldo, and J. Wrampelmeyer (2015). The euro interbank repo market. *The Review of Financial Studies 29*(7), 1747–1779.

Merrick Jr, J. J., N. Y. Naik, and P. K. Yadav (2005). Strategic trading behavior and price distortion in a manipulated market: anatomy of a squeeze. *Journal of Financial Economics 77*(1), 171–218.

Pasquariello, P. (2017). Government intervention and arbitrage. *The Review of Financial Studies 31*(9), 3344–3408.

Pelizzon, L., M. G. Subrahmanyam, R. Tobe, and J. Uno (2017). Quantitative easing, scarcity, and spotlight effects on liquidity in the government bond market. Unpublished working paper, Goethe University Frankfurt.

Pelizzon, L., M. G. Subrahmanyam, D. Tomio, and J. Uno (2013). The microstructure of the European sovereign bond market: a study of the eurozone crisis. Unpublished working paper. New York University, New York, NY.

Pelizzon, L., M. G. Subrahmanyam, D. Tomio, and J. Uno (2016). Sovereign credit risk, liquidity, and european central bank intervention: Deus ex machina? *Journal of Financial Economics 122*(1), 86–115.

Pericoli, M. and G. Veronese (2017). Monetary policy surprises over time. Unpublished working paper, Bank of Italy.

Schlepper, K., H. Hofer, R. Riordan, and A. Schrimpf (2017). Scarcity effects of qe: A transaction-level analysis in the bund market. Unpublished working paper, Deutsche Bundesbank.

Song, Z. and H. Zhu (2018a). Mortgage dollar roll. *Review of Financial Studies* (Forthcoming).

Song, Z. and H. Zhu (2018b). Quantitative easing auctions of treasury bonds. *Journal of Financial Economics 128*(1), 103–124.

Appendix

A.1 Identification of the CTD Bond

In the body of the paper, we focus the bond-market analysis on a single bond (i.e., the CTD bond that the short futures position is most likely to deliver). We identify the CTD bond for each contract following the calculations laid out in Subsection IV.B and Section V. That is, we calculate the mispricing between each bond and the corresponding futures contract as per Equation (1). While, in theory, the identity of the CTD bond could change through the life of the contract, because of changes in the shape of the yield curve or in the set of bonds eligible for delivery, such uncertainty is minimal in the sample we consider. In Table VII, we list the CTD bond per each contract in our sample, and show the percentage of minutes in the three-month contract duration that the bond we identify as CTD is indeed the cheapest among all deliverable bonds (% of CTD). We also report the percentage of contracts that were physically settled with the CTD bond (% of Delivered).

As shown in the table, the bond we identify as the CTD for a given contract is, on average, the one with the smallest basis 99.93% (95.67%) of the time for Germany (Italy), demonstrating that the uncertainty on the identity of the CTD was minimal. Moreover, when the short futures positions holder decides to physically settle their positions, they do so using the CTD bond 99.98% of the time for Germany (93.90% for Italy). As the short position could deliver any of the bonds in the deliverable basket, the fact that the CTD bond is delivered in the overwhelming majority of cases further supports our identification. This clear identification of the CTD bond also suggests that the Bund and BTP futures markets are not subject to squeeze potential in the period we consider. Merrick Jr, Naik, and Yadav (2005) studies the strategic trading around delivery of bond futures for the UK/ Gilt market and defines a full squeeze as the event that the CTD and the next CTD bond have the same (adjusted) price. If a squeeze happened in our sample, therefore, we should observe uncertainty as for the identity of the CTD bond, which does not seem to be the case.

To control that the identity of the CTD bond is known to market participants at the time of trade and not only ex-post, we plot the average frequency the bond we identify as CTD has the smallest basis at different times during the life of the futures contract in Panel A of Figure 9. The graph shows that the CTD has the smallest basis more than 90% of time, on average, already on the first day of trading (i.e., when there are 90 days to delivery).

Insert Table VII here.

Insert Figure 9 here.

The CTD bond is determined as the bond with the smallest basis. Considering Equation (1), it is clear that, everything else constant, the higher the conversion factor of a bond, the lower the associated basis. Conversion factors are calculated with complex formulas that can be found on the Eurex website, but can be approximated with high precision as the price the bond would have at delivery if the yield curve was flat at 6%, scaled by its face value. If yields are below 6%, as is the case during the period we consider, the conversion factor is higher, the smaller is the duration of the CTD bond, to a first approximation. Conversely, if yields are above 6%, the CTD bond will be that with the largest duration. It follows that the likelihood of the CTD's identity changing during the life of the contract is the highest when bond yields are near 6%. Panel B of Figure 9 shows the yield of the CTD bond in the period we consider. The yields are, generally, far from 6%, confirming that the identity of the CTD is known with certainty by market participants. The optionality to deliver the cheapest bond, called the quality option, is priced in the futures contract and can be priced following standard option-pricing models. While our calculations forgo the quantification of the value of such option, its value would be the highest in the first part of the sample, when yields are closer to the 6% level, and smallest during the QE interventions. As such, the analysis in the main body of the paper might overestimate the basis between 2013 and 2015 and underestimate it from 2015 and 2017. The omission of the option value, hence, biases our results against finding a larger basis during the QE intervention.

A.2 Descriptive Statistics

In this section, we report the descriptive statistics of the variable we employ in our analysis. Table VIII shows the average, standard deviation, and fifth, 25th, 50th, 75th, and 95th percentiles of the left- and right-hand-side variables in our specifications separately for Italy and Germany in Panels A and B, respectively. The top part of each panel features CTD bond characteristics (such as its yield to maturity and liquidity), while the bottom part of each panel shows country-specific variables, such as the amount of bonds held at the ECB, as a fraction of their outstanding amount, and the RFR index of the rate of repo transactions.

Insert Table VIII here.

We calculate the bonds' best bid and ask prices, and corresponding bid-ask spreads, at a one-minute frequency. We average the spreads at a daily level to calculate the bonds' illiquidity, BA_{it}^{B}, and we use the midquote to calculate the daily one-minute return standard deviation, σ_{it}^{B}. We average the midquote throughout the day to calculate the bonds' yield, $Yield_{it}$, and duration, $Duration_{it}$. In our analyses, we employ bond-specific characteristics, such as the bond's time to maturity, TtM_{it}, which varies discretely during the life of the bond, and the bond's original maturity $Maturity_{it}$ and outstanding amount $AmtIssue_{i}$. Since the identity of the CTD bond varies between contracts (see Table VII for the full list of CTD bonds by delivery), the variable $Maturity_{it}$ will discretely change as the CTD changes. That is, for example, the mean of $Maturity_{it}$ is an average of the original maturity of the CTD bonds weighted by how many days the bond was CTD: the bond with ISIN IT0004848831 will enter with a weight of $\frac{5*90}{17*90}$ since it was the CTD in 5 out of 17 BTP futures contracts. We calculate the volume of trading $Volume_{it}^{B}$ as the sum of quantities traded on the MTS platform for the CTD bond i on day t, in billions of euros. We show in Table VIII the descriptive statistics for repo transactions on CTD bonds. $CTDRepo_{it}$ is the median rate for overnight repo transactions on CTD bond i on day t, while $CTDRepoRange_{it}$ is the interquartile range of that distribution and $CTDRepo\sigma_{it}$ the corresponding standard deviation.

In the bottom of each panel, we report the distribution country-specific variables. The main right-hand-side variable in our analysis is the amount of bonds held by the ECB per each country, as a fraction of amount outstanding, $ECB_{it}^{\%}$. We also report the RFR index, RFR_{it}, the quantity-averaged overnight repo rate for country i on day t, calculated by RepoFunds, using data from the MTS Group and BrokerTec, and our replication of the index where we only include special transactions on the MTS platform, $\widehat{RFR_{it}}$.

Tables

Table I

Futures-Bond Basis and Quantitative Easing

This table shows the average daily mispricing between the futures contract and the underlying bonds for the whole sample and separately for the futures on German and Italian bonds. We report the average for the January 2013–February 2015 (i.e., before the QE intervention) and March 2015–April 2017 periods (i.e., during the QE intervention) separately. The basis is expressed as the difference between the forward bond price and the futures equivalent price, so that a positive basis implies that bonds are more expensive than the futures price would imply. We report the difference between the average basis before and during QE and the statistical significance of the corresponding t-test statistics by *, **, and ***, if the difference is significantly different from zero at the 10%, 5%, or 1% level, respectively. The basis is calculated according to Equation (1). In Panel A, we report the basis calculated at a one-minute frequency using midquotes for the futures and bond prices and the overnight EONIA for the riskless rate, and averaged throughout the day, $Basis_{it}$. In Panel B, we report the basis calculated using bid and ask prices for the bond and futures contract, respectively, and the median special repo rate as the cost for obtaining the bond, $TradeBasis_{it}$. In Panel C, we report the average maximum between $TradeBasis_{it}$ and zero, $Arbitrage_{it}$. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS and futures data are obtained for the Eurex market via Thomson Reuters.

Panel A: $Basis_{it}$			
	All	Germany	Italy
Before QE	0.007	0.031	−0.017
During QE	0.073	0.095	0.051
Difference	0.066***	0.064***	0.067***
Panel B: $TradeBasis_{it}$			
	All	Germany	Italy
Before QE	−0.037	−0.012	−0.062
During QE	−0.022	−0.002	−0.042
Difference	0.015***	0.010***	0.020***
Panel C: $Arbitrage_{it}$			
	All	Germany	Italy
Before QE	0.002	0.005	0.000
During QE	0.010	0.017	0.004
Difference	0.008***	0.012***	0.004***

Table II
Bond Market Illiquidity and ECB Bond Holdings

This table shows the results for the regression of the CTD bond's bid-ask spread for country i and day t, BA_{it}^{B}, on the fraction of bonds of that country that are held at the ECB, $ECB_{it}^{\%}$. We control for bond-specific determinants of liquidity: the nationality of the bond by including DE_i, a dummy that is one for the German contract and zero otherwise; the time to maturity of the bond, TtM_{it}, in years; whether the bond was a 15-year bond originally with the $Long_{it}$ dummy; the amount issued in billions, $AmtIssue_{it}$; the volatility of the bond returns, σ_{it}^{B}; and the bond's traded volume, $Volume_{it}^{B}$, in billions. Finally, we control for European market–wide funding liquidity conditions by using the value of the cross-currency basis swap spread $CCBSS_t$, a measure of dollar-denominated funding illiquidity. We substitute the left-hand side variable with its natural logarithm, $LogBA_{it}^{B}$, in Specification 5 and the average of the bid-ask spreads of the non-CTD deliverable bonds, BA_{it}^{Del}, in Specification 6. We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are two-way clustered at the bond and day level for Specifications 1 to 5 and 7, and at the delivery and day level for Specification 6. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS. $CCBSS_t$ rates are obtained from Bloomberg.

	(1) BA_{it}^{B}	(2) BA_{it}^{B}	(3) BA_{it}^{B}	(4) BA_{it}^{B}	(5) $LogBA_{it}^{B}$	(6) BA_{it}^{Del}	(7) BA_{it}^{B}
$ECB_{it}^{\%}$	0.189***	0.139**	0.146**	0.188***	2.134**	0.164***	0.077*
	(3.479)	(2.271)	(2.527)	(3.038)	(2.504)	(3.584)	(1.802)
DE_i	−0.044***	−0.034***	−0.034***	−0.033***	−0.472***	−0.052***	−0.003
	(−8.855)	(−3.448)	(−4.615)	(−4.292)	(−5.130)	(−9.315)	(−0.568)
TtM_{it}		0.012	−0.001	0.001	0.043		−0.002
		(0.703)	(−0.079)	(0.063)	(0.330)		(−0.268)
$Long_{it}$		0.009	0.013**	0.014**	0.126		0.019***
		(1.238)	(2.094)	(2.046)	(1.429)		(3.954)
$AmtIssue_{it}$		0.001	0.000	0.000	0.009		0.000
		(0.938)	(0.453)	(0.283)	(0.808)		(0.144)
σ_{it}^{B}			0.031***	0.031***	0.324***		0.005**
			(5.674)	(5.878)	(6.867)		(2.110)
$Volume_{it}^{B}$			−0.102***	−0.102***	−1.048***		−0.075***
			(−5.553)	(−5.533)	(−5.923)		(−4.538)
$CCBSS_t$				0.000	−0.002		0.000**
				(−1.127)	(−0.817)		(−2.098)
BA_{it}^{Del}							0.673***
							(10.131)
Adj. R^2	0.426	0.444	0.574	0.576	0.603	0.495	0.728
Obs	2116	2116	2116	2116	2116	2116	2116

Table III
Repo Rates and ECB Bond Holdings

This table shows the results for the regression of the CTD bonds' median daily repo rate for country i and day t, $CTDRepo_{it}$, on the fraction of bonds of that country that are held at the ECB, $ECB^{\%}_{it}$. We control for bond-specific characteristics: the nationality of the bond, by including DE_i, a dummy that is one for the German contract and zero otherwise; the time to maturity of the bond, TtM_{it}, in years; whether the bond was a 15-year bond originally with the $Long_{it}$ dummy; the amount issued in billions, $AmtIssue_{it}$; the volatility of the bond returns, σ^B_{it}; and the bond bid-ask spread, BA^B_{it}. We substitute the left-hand-side variable with the RFR, RFR_{it}, a quantity-weighted repo rate index calculated with transactions, both GC and special, involving sovereign government bonds and taking place on the MTS and BrokerTec platforms, and published by the NEX Group. We calculate an index, $\widehat{RFR}_{it}$, similar to RFR_{it}, which includes only special transactions. The dependent variable for Specification 4 (5) is the difference between $CTDRepo_{it}$ and RFR_{it} ($\widehat{RFR}_{it}$). We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are two-way clustered at the bond and day level for Specifications 1, 4, and 5, and at the delivery and day level for Specifications 2 and 3. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS. Repo transactions data are provided by the MTS Group, and the RFR is published by the NEX Exchange.

	(1) $CTDRepo_{it}$	(2) RFR_{it}	(3) $\widehat{RFR}_{it}$	(4) $CTDRepo - RFR_{it}$	(5) $CTDRepo - \widehat{RFR}_{it}$
$ECB^{\%}_{it}$	−6.759***	−4.644***	−5.239***	−2.107***	−1.449***
	(−19.796)	(−15.080)	(−14.682)	(−9.319)	(−5.496)
DE_i	−0.108***	−0.072**	−0.114***	−0.046	−0.021
	(−2.637)	(−2.414)	(−3.898)	(−1.457)	(−0.777)
σ^B_{it}				−0.003	0.012
				(−0.311)	(1.100)
$AmtIssue_{it}$				0.001	0.006
				(0.145)	(1.074)
BA^B_{it}				−0.225	−0.362*
				(−0.748)	(−1.717)
TtM_{it}				−0.019	−0.018
				(−0.515)	(−0.578)
$Long_{it}$				0.008	−0.038
				(0.285)	(−1.566)
Adj. R^2	0.808	0.818	0.811	0.420	0.274
Obs	2116	2116	2116	2116	2116

Table IV
Repo Rates Dispersion and ECB Bond Holdings

This table shows the results for the regression of the dispersion of the CTD bond's special repo rates, $CTDRepoRange_{it}$, defined as the difference between the 75th and the 25th percentile of the distribution of the CTD bond repo rates for CTD Bond-i on day$t$, on the fraction of bonds of that country that are held at the ECB, $ECB^{\%}_{it}$. We control for several bond-specific characteristics: the nationality of the bond's issuer, by including DE_i, a dummy that is one for the German contract and zero otherwise; the time to maturity of the bond, TtM_{it}, in years; whether the bond was a 15-year bond originally with the $Long_{it}$ dummy; the amount issued in billions, $AmtIssue_{it}$; the volatility of the bond returns, σ^B_{it}; and the bond bid-ask spread, BA^B_{it}. We substitute the left-hand-side variable with the standard deviation of the repo rates for the transactions of CTD Bond–i on day-t, $CTDRepo\sigma_{it}$, in Specification 3. We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are two-way clustered at the bond and day level. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS. Repo transactions data are provided by the MTS Group, and the RFR is published by the NEX Exchange.

	(1) $CTDRepoRange_{it}$	(2) $CTDRepoRange_{it}$	(3) $CTDRepo\sigma_{it}$
$ECB^{\%}_{it}$	0.678***	0.685***	0.563***
	(5.850)	(5.463)	(5.935)
DE_i	−0.003	−0.004	−0.003
	(−0.444)	(−0.377)	(−0.394)
σ^B_{it}		−0.002	−0.007
		(−0.346)	(−1.464)
$AmtIssue_{it}$		0.000	0.000
		(−0.038)	(0.227)
BA^B_{it}		0.028	0.087
		(0.174)	(0.742)
TtM_{it}		0.007	0.015
		(0.423)	(1.101)
$Long_{it}$		−0.005	−0.017
		(−0.408)	(−1.533)
Adj. R^2	0.161	0.160	0.174
Obs	2116	2116	2116

Table V

The Futures-Bond Basis and Quantitative Easing

This table shows the results for the regression of the different measures of mispricing and the arbitrage opportunity between futures and bonds on the fraction of bonds of that country that are held at the ECB, $ECB^{\%}_{it}$. The dependent variable in Specifications 1 and 2 is $Basis_{it}$, the mispricing calculated according to Equation (1), using the bond and futures midquotes as their prices and EONIA as the riskless rate. In Specification 3, we calculate the profits/losses an arbitrageur would incur if she was to sell the bond and buy the futures contract, $TradeBasis_{it}$. We calculate the profits by using the bond's bid price and the futures contract's ask price, and calculate the funding cost of the bond leg of the trade based on that bond's median special repo rate. In Specification 4, we modify $TradeBasis_{it}$ to only measure the frequency and magnitude of arbitrage profits, averaging the maximum between $TradeBasis_{it}$ and zero throughout the day to obtain the daily measure $Arbitrage_{it}$. All mispricing variables are calculated at a one-minute frequency and averaged across a day to create a daily series. We control for the pull-to-parity effect by adding the amount of days to delivery DtD_{it} as regressor. We also control for: the nationality of the contract with the dummy DE, which is equal to one if the contract is for a German bond and zero otherwise; the magnitude of the CTD bond's special repo rate, $CTDRepo_{it}$; the liquidity of the CTD bond by its bid-ask spread, BA^{B}_{it}; and the dispersion of the CTD bond's repo rate, as measured by the interquartile range of the distribution of the repo rate, $CTDRepoRange_{it}$. We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are two-way clustered at the bond and day level for the classical regression in Specifications 1, 2, and 3. Specification 4 is a Tobit regressions, censored at zero, since $Arbitrage_{it}$ is bound by zero. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS and futures data are obtained for the Eurex market via Thomson Reuters. Repo transactions data are provided by the MTS Group, and the RFR is published by the NEX Exchange.

	(1) $Basis_{it}$	(2) $Basis_{it}$	(3) $TradeBasis_{it}$	(4) $Arbitrage_{it}$
$ECB^{\%}_{it}$	0.817^{***}	0.283^{**}	0.188^{***}	0.319^{***}
	(10.781)	(1.996)	(5.014)	(4.249)
DE_i	0.036^{***}	0.036^{***}	0.043^{***}	0.027^{***}
	(4.935)	(5.125)	(8.264)	(2.894)
DtD_{it}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}
	(4.923)	(5.367)	(4.669)	(3.645)
BA^{B}_{it}		0.169		
		(1.311)		
$CTDRepo_{it}$		-0.070^{***}		
		(−3.083)		
$CTDRepoRange_{it}$		0.048		
		(1.516)		
Adj. R^2	0.619	0.661	0.392	
Obs	2116	2116	2116	2116

Table VI

The Futures-Bond Basis and Quantitative Easing

This table shows the results for the regression of the different measures of mispricing and the arbitrage opportunity between futures and bonds on a dummy variable that equals one when the ECB's QE is in effect, ECB_{it}. The dependent variable in Specifications 1 and 2 is $Basis_{it}$, the mispricing calculated according to Equation (1), using the bond and futures midquotes as their prices and EONIA as the riskless rate. In Specification 3, we calculate the profit/losses an arbitrageur would incur if she was to sell the bond and buy the futures contract, $TradeBasis_{it}$. We calculate the profits by using the bond's bid price and the futures contract's ask price, and calculate the funding cost of the bond leg of the trade based on that bond's median special repo rate. In Specification 4, we modify $TradeBasis_{it}$ to only measure the frequency and magnitude of arbitrage profits, averaging the maximum between $TradeBasis_{it}$ and zero throughout the day to obtain the daily measure $Arbitrage_{it}$. We also control for: the nationality of the contract with the dummy DE, which is equal to one if the contract is for a German bond and zero otherwise; the magnitude of the CTD bond's special repo rate, $CTDRepo_{it}$; the liquidity of the CTD bond by its bid-ask spread, BA^B_{it}; and the dispersion of the CTD bond's repo rate, as measured by the interquartile range of the distribution of the repo rate, $CTDRepoRange_{it}$. All quantities are calculated as the difference between the variable on day t and the value of the variable on the corresponding day-to-delivery of the previous delivery contract, which took place between 89 and 91 days prior, depending on the distribution of weekdays. We specify the difference transformation of the variables by preceding their name with Δ_{90}. We indicate the statistical significance of the parameters by *, **, and ***, if they are significantly different from zero at the 10%, 5%, or 1% level, respectively. Standard errors are two-way clustered at the day-to-delivery and day level. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. We lose 90 observations per country, as we cannot calculate the changes for the observations of the March 2013 contract. Bond price data and bond characteristics are obtained from MTS and futures data are obtained for the Eurex market via Thomson Reuters. Repo transactions data are provided by the MTS Group, and the RFR is published by the NEX Exchange.

	(1)	(2)	(3)	(4)
	$\Delta_{90}Basis_{it}$	$\Delta_{90}Basis_{it}$	$\Delta_{90}TradeBasis_{it}$	$\Delta_{90}Arbitrage_{it}$
ECB_{it}	0.019***	0.006***	0.006***	0.003***
	(10.187)	(3.539)	(3.738)	(4.998)
DE_i	0.001*	−0.002***	−0.001*	0.002***
	(1.695)	(−3.471)	(−1.752)	(3.888)
$\Delta_{90}BA^B_{it}$		0.147***		
		(4.079)		
$\Delta_{90}CTDRepo_{it}$		−0.097***		
		(−11.944)		
$\Delta_{90}CTDRepoRange_{it}$		0.027**		
		(1.985)		
Adj. R^2	0.032	0.273	0.003	0.008
Obs	1936	1936	1936	1936

Table VII

Cheapest-to-deliver Bonds

This table reports, per each contract delivery and country in our sample, the ISIN of the bond we identify as the cheapest to deliver. We report the frequency, in percentage terms of trading minutes per contract, for which the bond was the actual CTD (% CTD). We report the percentage of physically settled contracts that were settled with the bond we identify as the CTD (% of Delivered). Data on bond prices and repo rates employed to calculate the frequency of the CTD status of bonds are obtained from the MTS group. Data on the prices of futures contracts and the fraction of physically settled contracts are obtained from Eurex.

		Germany			IT	
Delivery	Bond	% CTD	% of Delivered	Bond	% CTD	% of Delivered
201303	DE0001135465	99.938%	100.000%	IT0004848831	99.686%	100.000%
201306	DE0001135465	99.669%	100.000%	IT0004848831	67.326%	100.000%
201309	DE0001135473	99.901%	100.000%	IT0004848831	97.086%	100.000%
201312	DE0001135473	99.966%	100.000%	IT0004848831	89.498%	77.664%
201403	DE0001102309	99.926%	100.000%	IT0004848831	99.802%	100.000%
201406	DE0001102309	99.965%	100.000%	IT0004898034	99.866%	98.753%
201409	DE0001102325	86.357%	100.000%	IT0004898034	99.893%	100.000%
201412	DE0001102325	99.966%	100.000%	IT0004356843	99.747%	100.000%
201503	DE0001102333	99.654%	99.934%	IT0004953417	99.532%	100.000%
201506	DE0001102333	99.910%	100.000%	IT0004953417	99.399%	100.000%
201509	DE0001102358	99.816%	99.751%	IT0004513641	98.875%	100.000%
201512	DE0001102366	99.562%	100.000%	IT0004513641	76.382%	19.908%
201603	DE0001102374	99.808%	100.000%	IT0004513641	99.657%	100.000%
201606	DE0001102374	99.059%	100.000%	IT0004513641	99.872%	100.000%
201609	DE0001102382	98.648%	100.000%	IT0004644735	99.895%	100.000%
201612	DE0001102382	99.558%	100.000%	IT0004644735	99.981%	100.000%
201703	DE0001102390	99.991%	100.000%	IT0004644735	99.935%	100.000%
Average		98.923%	99.981%		95.672%	93.901%
Median		99.816%	100.000%		99.686%	100.000%

Table VIII
Descriptive Statistics

This table shows the distribution of CTD bond-specific variables, together with a host of macro variables. Variables for Italian bonds are shown in Panel A. The corresponding quantities for German bonds are shown in Panel B. BA^B_t is the CTD bond bid-ask spread, σ^B_{it} is its return volatility, both based on observations sampled at a one-minute frequency. We employ the average bond price throughout the day to calculate $Yield_t$, the CTD's yield, and $Duration_{it}$, its duration. We report the CTD bond characteristics $Maturity_{it}$, its original maturity, TtM_t, its time to maturity, and $AmtIssue_{it}$, its amount issued in billions. We calculate $Volume^B_{it}$, the CTD's volume traded, by summing up all transactions at a daily frequency, and we express them in billions of euros of face values. $CTDRepo_{it}$ is the CTD bond daily median repo rate for overnight transactions, and $CTDRepoRange_{it}$ ($CTDRepo\sigma_{it}$) is the repo rate's interquartile spread (standard deviation). The table also shows the distribution for country-specific macro variables, at the bottom of each panel, such as the percentage of bonds held at the ECB as a result of its QE, $ECB^{\%}_i t$, the RFR index (i.e., the average repo rate for a generic repo transaction for that country, RFR_{it}) and our replication of the RFR index, $\widehat{RFR_{it}}$. Data on the ECB purchases were obtained from the ECB's website, the amounts of sovereign bonds outstanding were obtained from the websites of national central banks, and repo rate indexes were obtained from RepoFunds. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS. Repo transactions data are provided by the MTS Group, and the RFR is published by the NEX Exchange.

Panel A: Italy							
Variable	Mean	Std	P5	P25	Median	P75	P95
BA^B_{it}	0.093	0.036	0.047	0.069	0.085	0.111	0.161
$Yield_{it}$	2.444	1.128	1.154	1.470	2.091	3.542	4.428
$Duration_{it}$	7.573	0.241	7.174	7.414	7.553	7.729	8.013
$Maturity_{it}$	12.998	2.733	10.178	10.178	15.449	15.507	16.011
TtM_{it}	9.166	0.311	8.737	8.899	9.116	9.422	9.704
$AmtIssue_{it}$	22.276	1.775	20.071	20.733	21.378	24.719	24.799
σ^B_{it}	1.309	0.533	0.684	0.940	1.179	1.549	2.379
$Volume^B_{it}$	0.059	0.067	0.000	0.005	0.037	0.091	0.199
$CTDRepo_{it}$	−0.176	0.330	−0.750	−0.385	−0.090	0.080	0.250
$CTDRepoRange_{it}$	0.049	0.061	0.005	0.015	0.030	0.060	0.170
$CTDRepo\sigma_{it}$	0.047	0.051	0.008	0.016	0.032	0.059	0.140
$ECB^{\%}_{it}$	0.044	0.059	0.000	0.000	0.005	0.085	0.171
RFR_{it}	−0.231	0.295	−0.686	−0.519	−0.167	−0.010	0.119
$\widehat{RFR_{it}}$	−0.331	0.358	−0.910	−0.628	−0.230	−0.066	0.075

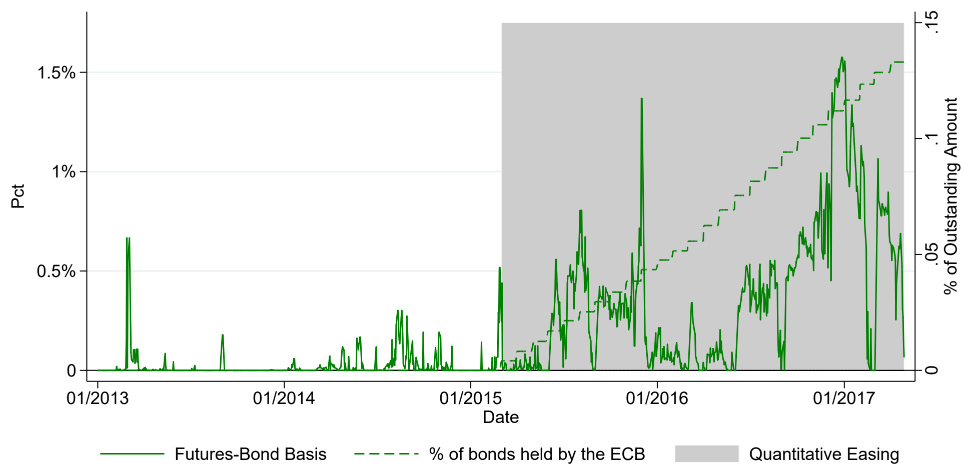
Panel B: Germany							
Variable	Mean	Std	P5	P25	Median	P75	P95
BA^B_{it}	0.052	0.018	0.032	0.041	0.049	0.056	0.091
$Yield_{it}$	0.702	0.605	−0.168	0.165	0.560	1.307	1.664
$Duration_{it}$	8.375	0.254	8.012	8.198	8.341	8.503	8.876
$Maturity_{it}$	10.075	0.087	9.932	10.052	10.093	10.099	10.238
TtM_{it}	8.911	0.147	8.696	8.795	8.901	9.027	9.164
$AmtIssue_{it}$	20.802	2.907	18.000	18.000	20.000	23.000	26.000
σ^B_{it}	1.028	0.290	0.673	0.837	0.971	1.150	1.540
$Volume^B_{it}$	0.001	0.006	0.000	0.000	0.000	0.000	0.005
$CTDRepo_{it}$	−0.364	0.440	−1.400	−0.675	−0.255	−0.040	0.165
$CTDRepoRange_{it}$	0.054	0.107	0.000	0.000	0.000	0.065	0.250
$CTDRepo\sigma_{it}$	0.053	0.083	0.000	0.000	0.023	0.064	0.210
$ECB^{\%}_{it}$	0.032	0.043	0.000	0.000	0.004	0.062	0.123
RFR_{it}	−0.105	0.232	−0.441	−0.342	−0.053	0.074	0.238
$\widehat{RFR_{it}}$	−0.155	0.232	−0.513	−0.388	−0.114	0.037	0.178

Figures

Figure 1. Central Bank Holdings of Sovereign Bonds and the Futures-Bond Basis

This figure shows the time series of purchases of sovereign bonds by the ECB and the contemporaneous mispricing between the bonds and the futures contracts that have the bonds as their underlying assets. In each panel (Panel A for Italy and Panel B for Germany), the full line represents the annualized return on the notional amount of €100 of an arbitrage strategy involving selling the bonds and perfectly hedging the position by buying the futures (on the left axis). The dashed line represents the bond held at the ECB as a fraction of the total amount of bonds outstanding (on the right axis). Data on bond purchases (outstanding) are obtained from the ECB (national central banks). Data on bond prices, characteristics, and repo rates involved in the arbitrage strategy are obtained from MTS, and data on the futures contracts are from Thomson Reuters. The QE period (i.e., when the ECB was actively purchasing bonds) is shaded in gray and starts in March 2015. The sample is based on 1,058 trading days for each of the two countries from January 2013 to April 2017.

A: Italy



B: Germany

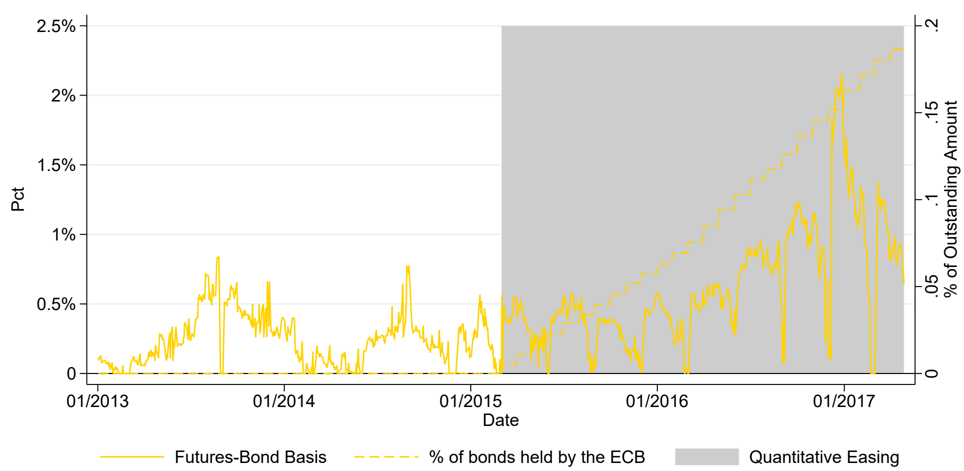
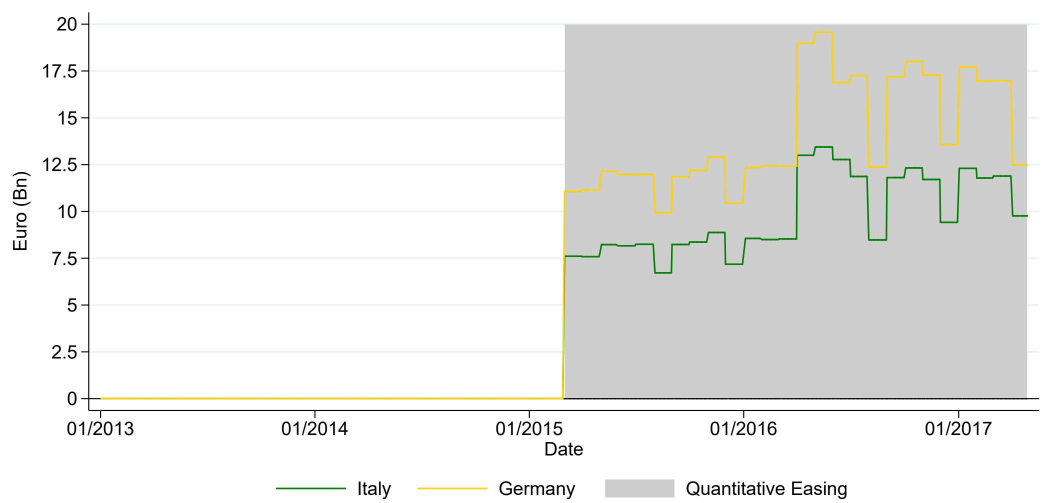


Figure 2. Central Bank Holdings of Italian and German Sovereign Bonds

This figure shows the time series of purchases by the ECB of Italian and German bonds. Panel A shows the monthly purchases of sovereign bonds, in billions of euros, while Panel B shows these purchases as a fraction of the total amount of bonds outstanding. Data for bond purchases are obtained from the ECB, while data on the amount of debt outstanding are obtained from the Bank of Italy and the Bundesbank. Data on the amount of outstanding German debt are released quarterly. The QE period (i.e., when the ECB was purchasing bonds) is shaded in gray and starts in March 2015.

A: Monthly Bond Purchases



B: Cumulative Bond Purchases as a Fraction of Outstanding Debt

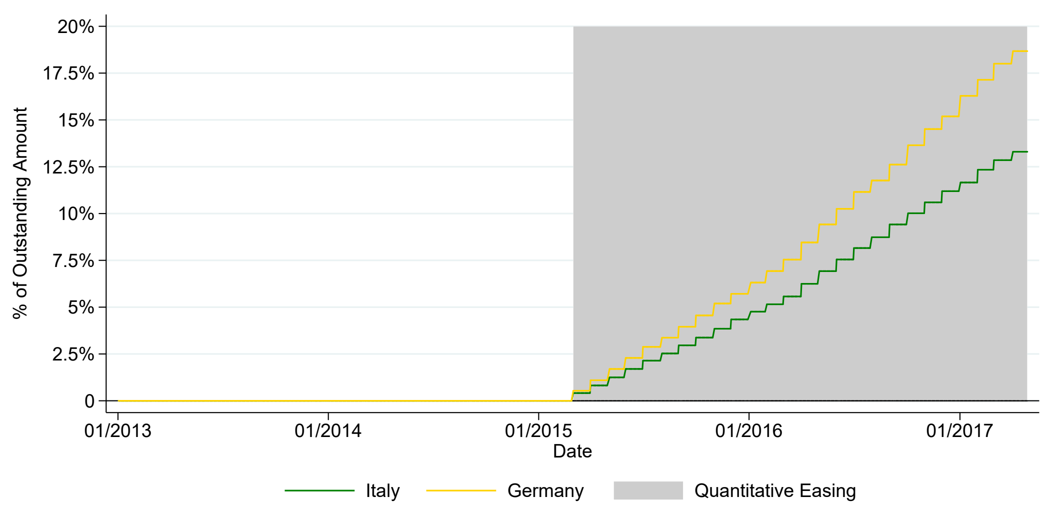


Figure 3. Mispricing between Bonds and Futures

This figure shows the time series of the mispricing between the futures contract and its underlying bond, for Germany (in yellow) and Italy (in green), $Basis_t$. The mispricing is calculated at a five-minute frequency according to 1 and averaged across the day, and is calculated in euros for €100 of bond face value. We employ midquotes for the bond and futures prices and the EONIA rate for the riskless rate. Bond data are obtained from the MTS group and futures data are obtained from Thomson Reuters for the Eurex market. The EONIA rate is from Bloomberg. Our sample extends from January 2013 to April 2017. The QE period (i.e., when the ECB was purchasing bonds) is shaded in gray and starts in March 2015. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS and futures data are obtained for the Eurex market via Thomson Reuters.

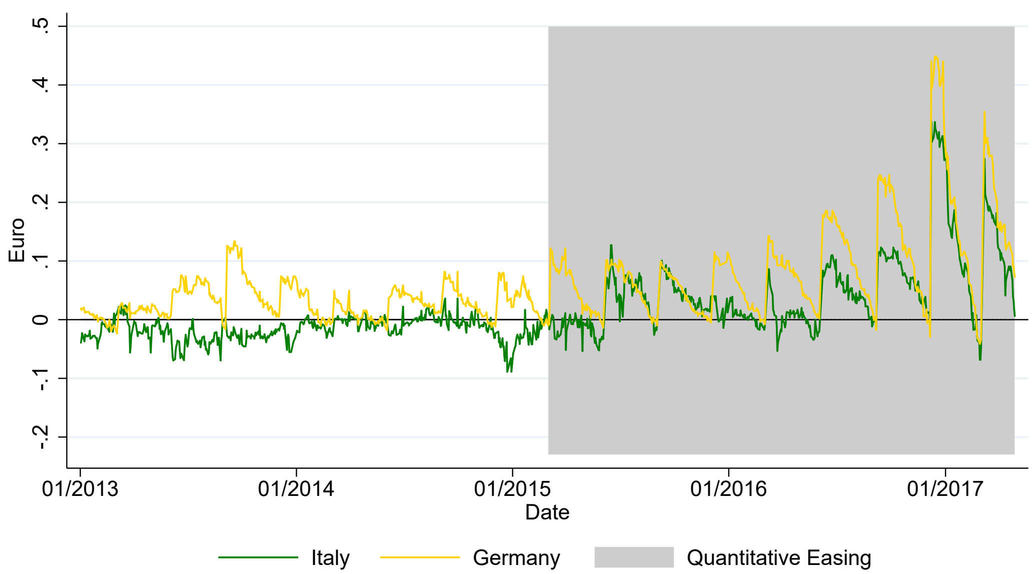


Figure 4. Half-life of a Shock to Bonds or Futures Prices

This figure shows the time series of the half-life of a shock to the prices of a futures contract or of its underlying bond, for Germany (in yellow) and Italy (in green), $HalfLife_{it}$. The half-life is calculated as $\frac{\log(0.5)}{\log(1+\alpha)}$, where α is the parameter of an auto-regressive system, $\Delta Basis_{it} = \alpha Basis_{t-1} + \epsilon_{it}$, and $Basis_{it}$ is the difference between the bond price and the futures price, appropriately scaled as per Equation (1). We estimate this specification for every hour of trading in our sample and obtain a daily half-life estimate series from the median α for country i and day t. Bond data are obtained from the MTS group and futures data are obtained from Thomson Reuters for the Eurex market. The EONIA rate is from Bloomberg. Our sample extends from January 2013 to April 2017. The QE period (i.e., when the ECB was purchasing bonds) is shaded in gray and starts in March 2015.

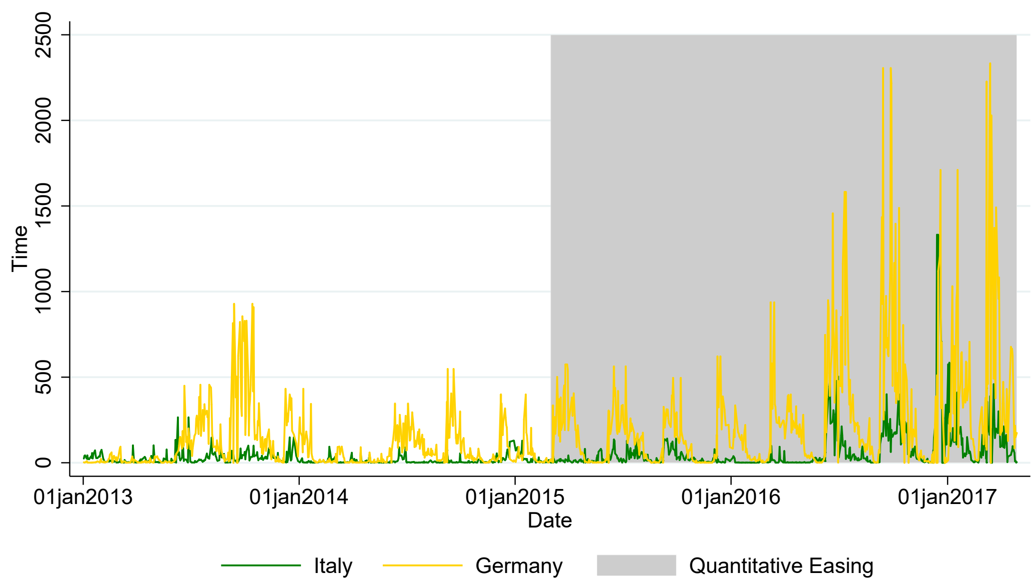


Figure 5. Bond Market Illiquidity

This figure shows the time series of the market illiquidity, measured by the bid-ask spread, for the German (in yellow) and Italian (in green) CTD bonds. We compute the bid-ask spread at a one-minute frequency and average it throughout the day. Bond data are obtained from the MTS group. Our sample extends from January 2013 to April 2017. The QE period (i.e., when the ECB was purchasing bonds) is shaded in gray and starts in March 2015. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS.

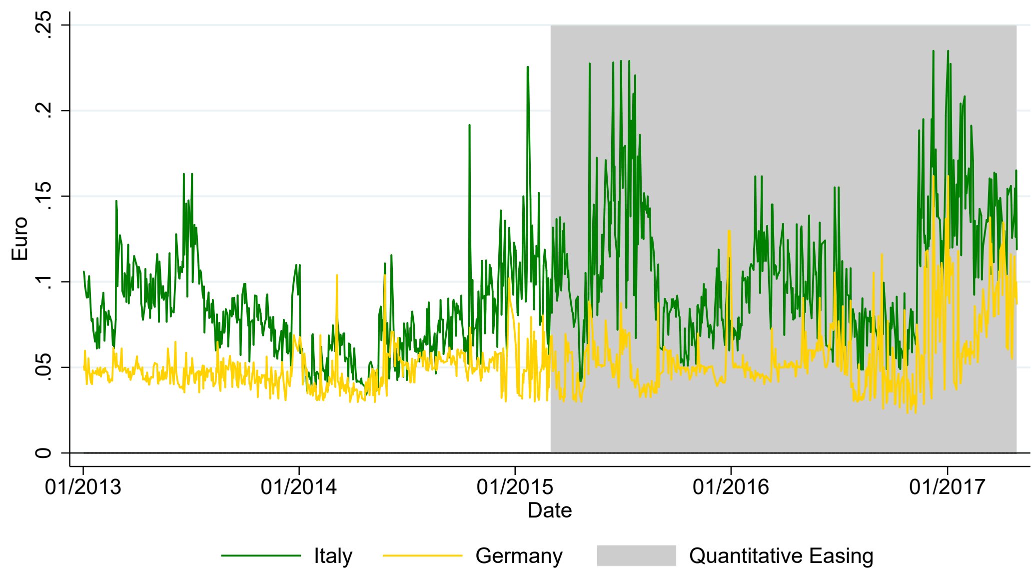


Figure 6. Bond and Index Repo Rates

This figure shows the time series of the daily special repo rates for the CTD bonds, measured as the median repo rate of all transactions with a one-day term, for the German (in yellow) and Italian (in green) CTD bonds, with a solid line. The RFR, a quantity-weighted index of repo rates for all GC and special transactions for sovereign bonds, are plotted as dashed lines for Germany and Italy, in yellow and green, respectively. The overnight EONIA rate is plotted in black. Bond and repo data are obtained from the MTS group. The EONIA rate is from Bloomberg. Our sample extends from January 2013 to April 2017. The QE period (i.e., when the ECB was purchasing bonds) is shaded in gray and starts in March 2015.

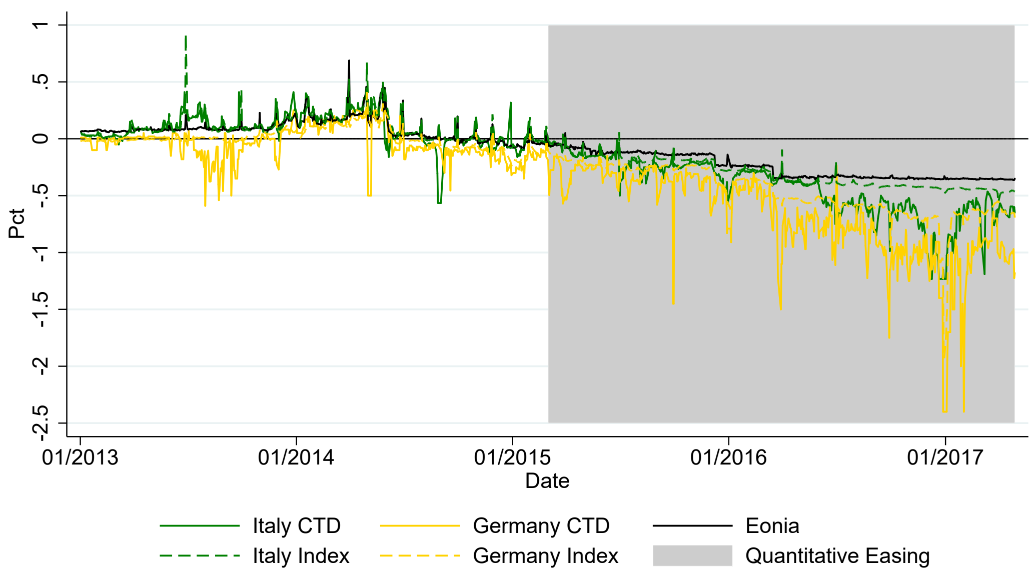


Figure 7. Repo Rate Dispersion

This figure shows the time series of the dispersion of the special repo rates for the CTD bonds, measured as the difference between the 75th and the 25th percentile of the distribution of the repo rates of all transactions with a one-day term, for the German (in yellow) and Italian (in green) CTD bonds. Bond and repo data are obtained from the MTS group. The EONIA rate is from Bloomberg. Our sample extends from January 2013 to April 2017. The QE period (i.e., when the ECB was purchasing bonds) is shaded in gray and starts in March 2015.

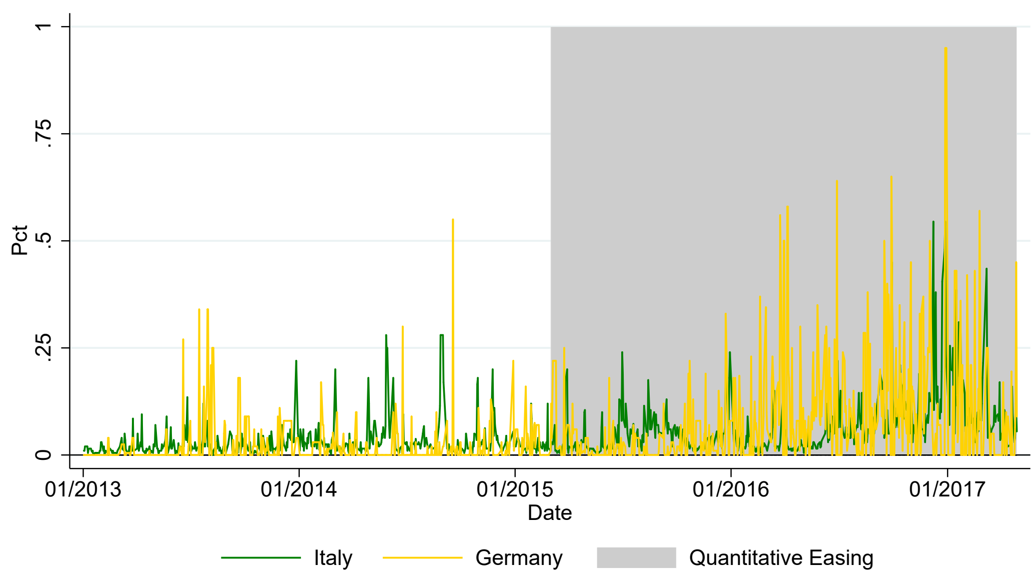
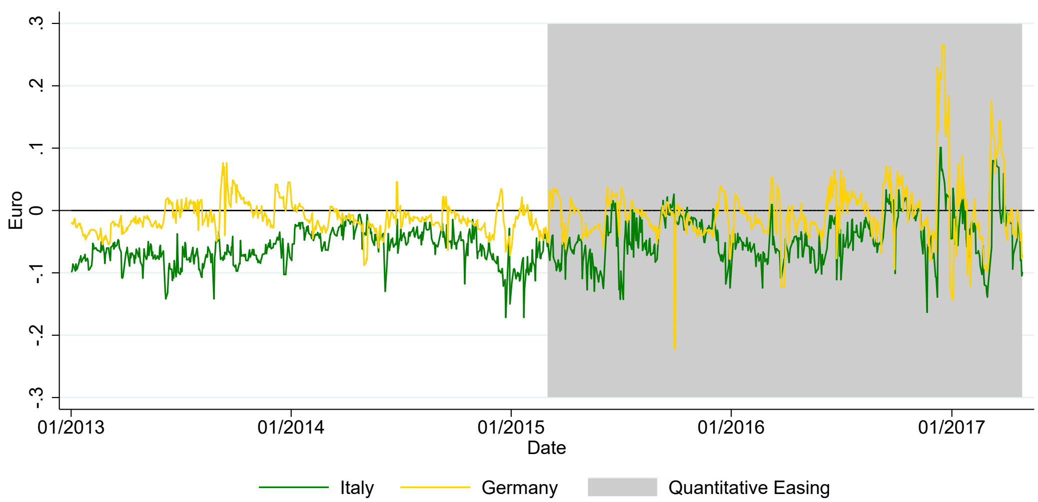


Figure 8. Futures-Bond Tradable Basis and Arbitrage Opportunities

This figure shows the time series of the actual arbitrage profit a trader would have made if she were to sell the bond and buy the corresponding futures contract for Germany (in yellow) and Italy (in green), $TradeBasis_t$. The tradable basis is calculated at a five-minute frequency according to 1 and averaged across the day, and is calculated in euros for €100 of bond face value. We assume the arbitrageur establishes the position by selling the bond at the bid price and buying the futures at the ask price. We assume the repo transaction needed to establish the bond position took place at the median special repo rate for that day. Panel A shows the unconditional average basis, while Panel B shows the average of the maximum between the tradable basis and zero, $Arbitrage_{it}$. Bond data are obtained from the MTS group and futures data are obtained from Thomson Reuters for the Eurex market. The repo rate is from the MTS Repo platform. Our sample extends from January 2013 to April 2017. The QE period (i.e., when the ECB was purchasing bonds) is shaded in gray and starts in March 2015. The sample is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS and futures data are obtained for the Eurex market via Thomson Reuters. Repo transactions data are provided by the MTS Group, and the RFR is published by the NEX Exchange.

A: $TradeBasis_{it}$



B: $Arbitrage_{it}$

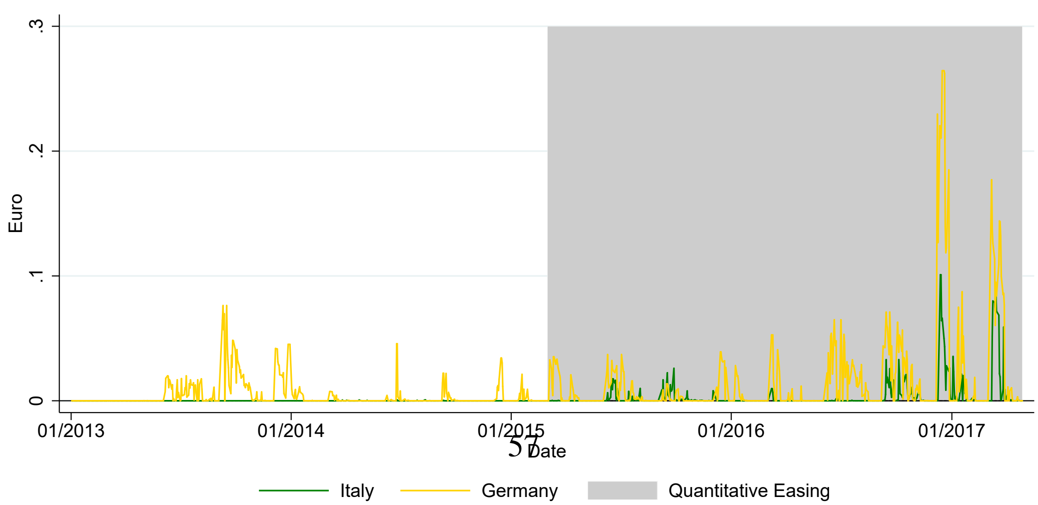
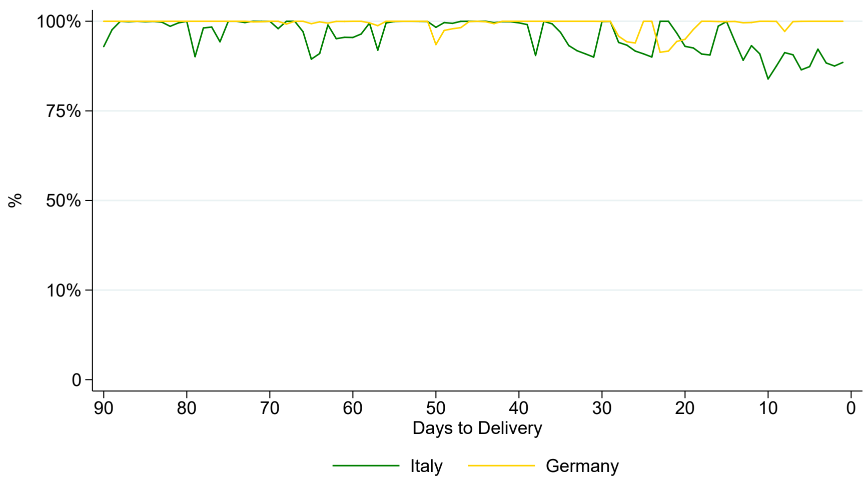


Figure 9. Cheapest-to-Deliver Frequency, Days to Delivery, and Yield

Panel A of this figure shows that the frequency the bond we identify as CTD has the smallest basis at different times during the life of the futures contract, averaged across all 17 contracts in our sample, and Panel B shows shows the yield to maturity of the bond we identify as CTD. We report the amount separately for Germany (in yellow) and Italy (in green). We calculate the basis in every trading minute in our sample, following Equation (1). The sample we employ is based on high-frequency quotes from 1,058 bond-days in our sample for each of the two countries, Germany and Italy, from January 2013 to April 2017. Bond price data and bond characteristics are obtained from MTS and futures data are obtained for the Eurex market via Thomson Reuters. The overnight EONIA and $CCBSS_t$ rates are obtained from Bloomberg. Repo transactions data are provided by the MTS Group, and the RFR is published by the NEX Exchange. Bond price data and bond characteristics are obtained from MTS.

A: Cheapest-to-Deliver Frequency and Days to Delivery



B: Cheapest-to-Deliver Yield