

Central Bank–Driven Mispricing*

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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 effects 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.

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I Introduction

Open market operations—the outright purchase of securities by central banks—are a traditional tool of standard economic policy, employed by monetary policy makers 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). Since March 2015, the European Central Bank (ECB) has purchased € 60 to 80 billion worth of sovereign bonds a month from March 2015 onwards, 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, the ECB states that it particularly designed its QE program 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, keep the market free from mispricing or arbitrage, preserving the law of one price. In other words, the ECB intended that the bond purchases should 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 equilibrium should not be hindered by the conduct of the central bank and their actions should not 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

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 U.S. Treasury bonds between March 2009 and September 2011, and the Bank of England purchased £ 463 billions worth of U.K. 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. The Bank of England, European Central Bank, and Bank of Japan continue to purchase bonds to this date, but have hinted at ending the programs. The U.S. Federal Reserve System is on its way to gradually disposing of its large holdings of U.S. Treasury bonds.

bonds' *relative* pricing?

To answer these questions, we focus on one of the the most straightforward arbitrage relationships in the fixed-income realm: that between the cash bond and corresponding futures. We show that the mispricing between cash bonds and futures caused by, and thus the welfare cost of, 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).² 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 € 60 to 80 billions a month, 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.e., i) transaction, ii) borrowing, and iii) roll-over costs, and show that the mispricing is still present in the market after these adjustments, indicating the actual trading profits arbitrageurs effectively left untapped. Transaction, borrowing, and roll-over 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:

"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

²By 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.

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.”

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 interest to the ECB and, thus, motivates the specific mispricing we focus on in our analysis.

The ameliorative effects that unconventional monetary policy interventions had on the level of interest rates have been the object of the extant academic literature (Krishnamurthy and Vissing-Jorgensen, 2011; Joyce, Lasao, Stevens, and Tong, 2011; Gagnon, Raskin, Remache, and Sack, 2011; Christensen and Rudebusch, 2012; D’Amico and King, 2013; Trebesch and Zettelmeyer, 2014; 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 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 act as a direct metric for comparison. We investigate whether, by only purchasing 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 a rigorous (as opposed to statistical) 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 to base our potential profit calculations on, contrary to arbitrage trades involving other derivatives, e.g., the basis trade between a corporate 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 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 the sovereign cash bond-futures arbitrage, which allows us to make a statement which, since it holds for a low-cost, rigorously-defined arbitrage, can be generalized to less obvious arbitrages that might involve even higher costs.³

Following our interpretation of Cœuré (2015), we identify an indicator of the suppression of the price discovery mechanism as the presence of a mispricing between the bond and futures prices. 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 market participants can only assess that the “true price” of the bond lies between the mid-quote of the bond and that of the futures contract (more precisely, within their bid- and ask-quotes), instead of identifying it as a single point-estimate. However, trading, borrowing, and roll-over 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

³While 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 mid-point, for example from one of their 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.

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' well-functioning 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. Finally, iii) the costs of QE interventions, and the resulting negative welfare implications, increase in how much the ECB over-pays for the assets it purchases: the mispricing measure, ignoring transaction and borrowing costs, therefore, represents a better estimate of such over-payment 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.

In the discussion of our findings, we hypothesize that regulatory capital constraints and, specifically, the minimum required return they imply—even on a riskless trade, because of the regulatory capital it employs—are consistent with the mispricing we observe on the market. 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 the market for interest rates, and rely on market participants to close the interest rate pricing gap. The pre-condition 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. In sum, interventions targeting a single asset class cannot be market-neutral, if capital constraints bind the arbitrageurs. Finally, we offer a simple policy implementation strategy that would improve the welfare impact of QE, 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, in general, regulators for two reasons. First, as articulated in the speech by Cœuré, central banks value the informativeness of financial markets: 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 position 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 measures 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 tax payers to arbitrageurs, i.e., financial institutions, and hence a matter for concern.

The paper is organized as follow. In Section II we highlight the papers our work is most 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 trade we study 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 which focuses on their unintended consequences, ranging from the effect on the 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

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 based on Kyle (1985), 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. This 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). His 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, 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 unattainable when considering interventions on the foreign exchange market. Therefore, 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.

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.⁴ Moreover, the unconventional monetary policy they consider, the Long Term Refinancing

⁴See Augustin, Chernov, and Song (2018) and Lando and Nielsen (2018) for recent work explaining why the spreads differ for sovereign

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 mid-quotes 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, Tepper, and Verdelhan (2018) analyze deviations of the covered interest rate parity and focus on how it is affected by bank capital requirements, which we only marginally touch upon in the discussion of our results.⁵

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 jaw-boning 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) Long Term Refinancing Operations or 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 or 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, i.e., a large scale asset purchase program focused on government bonds (Public Sector Purchase Program, or 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 was scheduled to last up to September 2016, but

CDS contracts quoted in different currencies, based on the correlation between sovereign default and currency depreciation.

⁵Contributing to the mispricing literature in fixed-income markets, Feldhütter (2012) shows corporate bonds can trade contemporaneously at different prices, depending on the identity of the buyer, with large traders trading at better prices.

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 € 60 billion a month, which was increased to € 80 billion between April 2016 and March 2017, when it was scaled back to € 60 billions. The scale, scope, and duration of the PSPP is unprecedented in the ECB's 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.⁶

The monthly euro amount available for bond purchases is allocated across countries to reflect that 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 what was done by the FED and Bank of Japan, who 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 euro, according to data obtained from the ECB.⁷ 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. 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, i.e., 15% of their outstanding amount.⁸ Accordingly, Panel B of Figure 2 shows the percentage of 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

⁶Eser and Schwaab (2013) show that the SMP lowered the level and volatility of yields in the targeted countries, and provide a detailed description of the analysis, 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.

⁷The breakdown of the monthly purchase quantities and duration by country can be found at <https://www.ecb.europa.eu/mopo/implementation/omt/html/index.en.html>.

⁸The ECB purchased both central and government bonds. For Italy, local bonds make up a minuscule amount of the total purchased. For Germany, on the other hand, local government bonds make up for about a quarter of all public debt. The ECB purchased the same relative amount of central and local debt.

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).⁹ We focus on two countries, one of which, Germany, is a so-called “core” country, while the other, Italy, belongs to the European “periphery”, with the goal of verifying 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 of the trading day, avoiding problems of non-synchronicity that several prior studies faced.

IV.A The Cash and Repo Bond Markets

Prices 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 inter-dealer 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 during our period of study.¹⁰

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

⁹While two other European countries, France and Spain, also have traded futures contracts, their markets are significantly less developed and less liquid than their Italian and German counterparts. Further, the history of government bond futures trading in Spain is relatively short.

¹⁰We 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.

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 BrokerTec, of the NEX Group. We obtain data detailing all special repo transaction taking place on the MTS Repo platform, including their rate, timing, term, and settlement. We also employ the RepoFunds rate index, a daily index published jointly by BrokerTec and MTS, which is a quantity-weighted average of all special and general collateral transactions involving German or Italian bonds. We use the RepoFunds rate 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, i.e., a contractual obligation, whereby the seller of the futures contract agrees to deliver a bond to the buyer, on or before 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 8.5 to 11 (10.5) years and an original maturity of no longer than 16 (11) years.¹¹ The bonds that are eligible to be delivered into the futures contract can, therefore, differ markedly, as to their coupon, time-to-maturity, and, therefore, price. To obviate the seller’s incentive to shortchange the 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, i.e., its conversion factor, is determined as the price (as a fraction of face

¹¹There are futures contracts also on the short and medium term bonds, i.e., bonds with time to maturity of two and five years, traded on the Eurex. However, these contracts tend to be much less liquid, in general, and therefore are not analyzed here.

value) that the bond would have, at delivery, if the term structure was flat at 6%.¹² 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 multiple factors ranging from supply- and demand-side considerations, e.g., 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, i.e., 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 et al. (2005).¹³ Futures contracts have deliveries on a quarterly basis, in March, June, September and December and, while three futures contracts with up to 9 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.¹⁴

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 owned by the Deutsche Börse group. Eurex offers traders a continuous, electronic trading platform, where liquidity is provided by market participants. In contrast to sovereign bonds, Euro-zone government bond futures contracts only trade on exchanges, namely on the Eurex and, more sparsely, on the Intercontinental Exchange (ICE). The coverage of our data on futures contracts, therefore, is almost complete.¹⁵ Subsection IV.B offers a primer on the functioning of government

¹²For 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.

¹³The 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.

¹⁴While 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.

¹⁵To the extent our data are less than complete, the quotes we use would be conservative and the arbitrage opportunities we identify would

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 follow:

- 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 basis for day t , and trading minute m as:

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

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, AC_{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. 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

be biased downward.

average mispricing across the 380 trading minutes of the particular trading day, $Basis_t = \frac{\sum_{m=1}^{380} Basis_{m,t}}{380}$.¹⁶

Figure 3 shows the time series of $Basis_t$, the mispricing per € 100 of bond face value, for German and Italian futures contracts, in yellow and green, respectively, between January 2013 and April 2017. 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 mid-quote of bond and futures prices, assuming that the bonds and futures contracts can be traded at a better price than indicated by the bid- and ask-quotes, and that the bond can be borrowed at the risk-free rate, which we approximate with the Euro OverNight Index Average (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 on the mispricing of the ECB intervention—the relative increase in bond prices compared to their futures counterpart following the central bank’s 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 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 and would be useful for someone trading the

¹⁶The 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. In the time period we consider, yields are far away from that level, making the value of the optionality negligible. Furthermore, ignoring the value of the optionality *overstates* the price of the futures contract and, hence, understates the basis. In other words, ignoring the value of the quality option goes against the likelihood of our finding a positive basis.

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 euro 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. To test and quantify the effects 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 show 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 futures contract and that of the underlying bond, which is shown in Figure 3. To do so, we analyze the direct and indirect mechanisms through which the ECB aimed to affect bond prices and the frictions it sought to leave unaffected, following the guidelines laid out by Cœuré (2015), as 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. This is the *direct* effect of the ECB’s QE, through scarcity and price pressure, on the relative pricing of bonds being purchased. In a frictionless market, this direct effect would be the sole channel for the impact of ECB purchases on bond prices. Such a direct effect, in a world with unlimited capital available at the risk-free rate and with no transaction costs, 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 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 mid-quotes for the bond and futures contract can be significantly different, even if an arbitrage trade were unprofitable, once trading costs are considered. For example, on January 6, 2016, the mispricing measure $Basis_{it}$ for Germany is € 0.09, while the arbitrage profit measure $Arbitrage_{it}$, which we define in Subsection VI.D, is zero, as arbitrage costs sum up to more than 9 euro cents.

We proceed as follow: 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 mispricing 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 will be available for purchases to traders, the turnover of the bonds will decrease, 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 holds on to a larger and larger fraction of available bonds, institutions with a need for highly liquid collateral securities will be willing to pay more to acquire them, decreasing the corresponding repo rate and contributing to the bonds' shortage. Finally, 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.¹⁷ On the one hand, the outright purchases could make market makers more willing to take on inventory risk and purchase bonds from their customers, hence 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 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 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 on their inventory for a longer period. A risk-averse market maker would, therefore, only buy it at a discount, worsening the liquidity they offer to their customers.

The effect the intervention has on market liquidity is important to assess the relative pricing of the cash bonds with respects to the futures contract: if we consider the ability 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 a trader from successfully conducting the replicating strategy. Alternatively, we can think of the profitability of arbitrage trades, which is negatively affected by market illiquidity, because the price at which the bond can be sold at, i.e., the bid-price, is further away from the bond mid-quote, so that the likelihood that a profitable arbitrage opportunity arises, assuming that the arbitrageur is forced to pay the 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 mid-quotes of the cash bond and the futures contract can diverge even more significantly, increasing

¹⁷D'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.

the range of possible relative prices.

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 innate 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 , on the fraction of bonds of that country that are held at the ECB, $ECB_{it}^{\%}$. 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), by including a dummy, DE_i , that is one for a German asset 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 $Long_i$ dummy (15-year bonds, which are deliverable into the Italian futures contract, are generally less liquid than their 10-year counterparts, the benchmark maturity); the amount issued, in billions, $AmtIssue_i$; the volatility of the bond returns, σ_{it}^B ; 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.¹⁸ Pelizzon et al. (2016) shows that, after 2012, funding liquidity measured by the $CCBSS_t$ is a good predictor of bond market liquidity. Omitting this variable would result in attributing to the ECB intervention the effect that funding liquidity had on market liquidity.

We report the results of the regression in Table II. 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.

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, increases the bid-ask spread by 1.9

¹⁸This 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 friction-less market, the CCBSS should be near zero. In fact, it has been consistently different from zero since the Great Recession.

euro 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 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. 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 increases the bid-ask spread, on average, by 21%, consistent with the previous specification.¹⁹

With a lack of 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.²⁰ 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. However, as shown in Specification 7, the ECB purchases had a more 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 Eq. 1 is not an accurate representation of an arbitrageur's profits is that we may have possibly 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

¹⁹We 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 (Pelizzon et al., 2013).

²⁰D'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.

basis, hence overestimating (underestimating) the arbitrageur's profits (losses) from lending money against the CTD bond. Figure 6 shows the overnight EONIA rate, the RepoFunds rate for Germany and Italy (dashed)—a quantity weighted repo rate index calculated with transactions, both general collateral (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. The daily measure of special repo rates for the CTD bonds are calculated as the median special repo rate from all transactions taking place on the MTS platform for the CTD bonds.²¹

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 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 RepoFunds rate (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 are held at the central bank, institutions looking for collateral are 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, towards 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, as expected from the exclusion of GC transactions, it is still higher than the repo rate commanded by the CTD bond, as shown in Table III.

Insert Table III here.

²¹We restrict the trades we consider 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. RepoFunds rates are quantity-weighted averages of GC and special transactions that satisfy similar requirements.

In Table III 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. Specification 1 shows that a 1% increase in the holding of sovereign bonds at the ECB decreases the interest rate earned from lending money against the CTD bond by 6.76 bp. 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), 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.²²

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

The naïve mispricing in Eq. 1, while technically correct, assumes the existence of a term repo market, i.e., a market where 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 moves against the position over the life of the trade.²³ Similarly, an arbitrageur rolling over her short bond position would be exposed to the roll-over 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. Hence, while we show in Subsection VI.B that ECB purchases affect the *level* of the repo rates, the scarcity they create can affect 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

²²Repo 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 hypotheses of absence of a unit-root in the series, for either country. That is, the trends in Figure 6 are of a deterministic fashion, around ECB holdings, and not of a stochastic one.

²³This is analogous to the effect of convexity in swap futures-spread analyzed in Gupta and Subrahmanyam (2000).

profitability of arbitrage trades), we calculate the dispersion of the repo rate of the 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, and regress it on the amount of bonds held at the ECB and bond-specific variables, reporting the results in Table IV.

Insert Table IV here.

Specification 1 shows that a 1% increase in the quantity of bonds held at the central bank increases the dispersion in repo rates by 67.8 bp, 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 roll-over 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 roll-over 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 borne by her. We select $RepoRange_{it}$ as a measure of roll-over 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 the mean 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 regress 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 . This specification shows that a 1% increase in bond holdings increases the mispricing between bonds and futures by € 0.8 cents.²⁴ 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.

²⁴On 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.

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. 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 increases 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 of Table V— BA_{it}^B , $CTDRepo_{it}$, and $CTDRepoRange_{it}$ —with the parameters for ECB_{it}^{QE} in Tables II, III, and IV. The bond liquidity channel, therefore, contributed to $\frac{0.189 \cdot 0.169}{0.871} = 4\%$ of the total effect of the ECB's QE on the mispricing, the repo rate channel contributed for $\frac{(-6.759) \cdot (-0.074)}{0.871} = 57\%$, and the repo rate uncertainty channel contributed for $\frac{0.678 \cdot 0.048}{0.871} = 4\%$.

Insert Table V here.

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, 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., $\Delta_{90}Basis_{i,t} = Basis_{i,t} - Basis_{i,t-90}$. This approach allows us to sidestep the pull-to-delivery effect that would complicate the analysis of the first-differenced variables and focus on the contribution of the ECB intervention to the basis. To reflect the imposed 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}^{QE} in Table V, indicating that our findings are robust to varying the statistical set-up.

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. 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’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 8.²⁵ 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, i.e., 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 $Arbitrage_{it}$ 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 show 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

²⁵This 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 inter-dealer 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.

$TradeBasis_{it}$ on the amount of bonds held at the ECB, in Specification 3 of Table V, showing that a 10% increase in bonds held at the central bank increases 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 the regression parameters, into a € 1.43 cents higher mispricing, after frictions have been taken into consideration. We regress $Arbitrage_{it}$ on $ECB_{it}^{c\%}$ in a Tobit setting in Specification 4 of Table V, which shows that the fraction of bonds held at the central bank, $ECB_{it}^{c\%}$, is statistically significant at the 1% level in explaining the probability of seeing untapped arbitrage opportunities and their magnitude.²⁶ We repeat the analyses using 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 is unchanged.

While the mispricing implied by $Basis_{it}$, shown in Figure 3, signifies that the price discovery process was significantly perturbed by the QE, finding 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 persistent presence of actual 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 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 conversation with market participants suggests that this premise ignores the possibility that regulatory requirements on 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.

²⁶The larger parameter for $ECB_{it}^{c\%}$ 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 observing a non-censored, i.e., positive, 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.

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, 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 obtained by considering how complying with Basel-mandated leverage ratio constraints, usually the binding constraint, in fact, affects the required return of the trade. Basel III (and its national equivalents) introduced a non-risk-based leverage ratio, obtained by dividing Tier 1 capital by the bank's average total consolidated assets, which banks must keep above 3%, or 5%, if they are systemically important.²⁷ 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 $10\% \cdot 5\% = 50\text{bps}$. Such regulatory considerations, therefore, raise the annual required return, even on a riskless arbitrage trade, from zero to 50bps.²⁸

To gain some intuition regarding how such a minimum required return can 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 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 50-bps, the basis needs to be at least $\text{€} \frac{50\text{bps}}{4} 100 = 0.125$ before the trade is profitable, in a capital-adjusted sense. Panel B

²⁷AFME (2012) provides a list of the market makers member 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.

²⁸This 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 risk 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 et al. (2018) show that leverage ratio-implied costs keep the covered interest rate parity from holding. Fleckenstein and Longstaff (2018) quantifies that on average, “balance sheet constraints add 81 basis points to intermediary funding costs”, and that this estimate is larger during periods of crisis.

of Figure 8 shows that the tradable basis exceeded € 0.125 on but a handful of days in our sample, and solely for the German sample. (It should be emphasized that all our computations in the tables and figures are based on daily *averages* of the basis measured on a minute-by-minute basis. Hence, our calculations are exceedingly conservative in the sense that on a given day, there may have been a few highly profitable trading minutes and several others that had virtually no or even negative bases, but are not reflected in our daily representations in the tables and figures.)

The presence of regulatory requirements can explain why we observe arbitrage opportunities and speaks to the feasibility of a market-neutral central bank intervention. Capital requirements were present both prior to, and during, the interventions; yet, we only 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 by 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 value-at-risk limits based on bank regulatory capital requirements creates the possibility of a tradable basis.²⁹

VIII.B Welfare Impact

Quantifying the welfare impact of central bank interventions is an economist's Gordian knot, given their far-reaching implications for the various agents' portfolio allocation and consumption decisions, and the absence of a clear counter-factual. Fortunately, the arbitrage trade we consider, however, allows us to calculate a particular component of welfare, i.e., the losses the central bank incurred as it *over-paid* for the CTD ten-year German and Italian bonds.³⁰ This calculation does not require us to explicitly lay out a counterfactual, since we draw our conclusions from the relative pricing of the bond with respect to the futures contract (the basis), and not its absolute deviation from a "natural" level.

If we assume that 1) the ECB either could have purchased the bonds at the mid-point (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

²⁹One may well ask why an unregulated entity such as a hedge fund does not take advantage of the profitable arbitrage and the answer is that the counter-party in the cash bond borrowing/repo transactions is likely to be one of the major banks, who would again be bound by the same regulatory frictions.

³⁰In contrast, Song and Zhu (2018b) show that the Federal Reserve *under-paid* for the bonds they purchased in the context of its QE.

observe for the CTD bonds can be generalized for all bonds targeted by the ECB, we can gauge how much the ECB over-paid for the assets by taking an appropriate multiple of the mispricing we report in Panel A of Table I. A $Basis_{it}$ of € 7.3 cents 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 the same basis or something similar 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 2017.³¹ We can obtain a welfare loss estimate by considering the regression parameters in Table V, which yield a similar 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 fractions of bonds held at the ECB on average over the sample period.

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 most bonds. While it is entirely possible that the assumption leads us to over-estimate the potential social welfare loss, it is also true that the CTD bonds we consider are often the 10-year on-the-run bonds and, thus, 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 under-estimate 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, identifying our welfare loss estimate as a lower bound.

The welfare loss stemming from impeding the price discovery process is clearly substantial, and exceeds 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 market and it, suggesting that designing truly market-neutral interventions should be an important goal for central banks going forward.

³¹ <https://www.ecb.europa.eu/pub/pdf/annrep/ecb.annualaccounts2017.en.pdf>.

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 functioning properly.

While regulatory requirements serve broader purposes of ensuring the banking system's soundness, the detailed workings of open market interventions need to 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, yet bond futures purchases do not affect the scarcity of the cash market. A larger cash bond availability would not hinder the working of the repo market and would not affect the market liquidity of cash bonds as much. 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 focused 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 auction or outright purchases, central banks have traded derivatives in prior instances, e.g., 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).

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 thus affected the mispricing both directly, through the price pressure

resulting from the demand applied to the bonds, and indirectly, through the effect of the bonds' scarcity on the repo market and its own liquidity.

We account for the costs that an arbitrageur would face when taking advantage of the relative mispricing, i.e., transaction, borrowing, and roll-over costs, and show that the untapped arbitrage opportunities are still present in the market. The arbitrage component, however, makes up between 3% and 10% percent of the mispricing, indicating that most of the dislocation in the price discovery process took place through the effect of the QE on the liquidity of the bond market and the cost of funding the position on the repo market. The mispricing we observe in the futures-bond arbitrage and others akin 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 tax payers to arbitrageurs, i.e., financial institutions, and needs to be examined more closely.

In terms of policy implications, 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 and achieve market neutrality by purchasing a broad set of assets.

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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 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 short futures positions holder decide 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 U.K./ 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 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 of the contract, 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 a 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 the identity of the CTD changes during the life of the contract is the highest when bond yields are near 6%. Figure 10 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 over-estimate 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.

Insert Figure 10 here.

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, liquidity, etc, 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 RepoFunds rate 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 mid-quote to calculate the daily one-minute return standard deviation, σ_{it}^B . We average the mid-quote 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 changes 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 RepoFunds rate index, $RF R_{it}$, 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, $\widehat{RF R}_{it}$.

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 the March 2015-April 2017 period, 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 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 mid-quotes 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. The overnight EONIA and $CCBS_t$ rates are obtained from Bloomberg. Repo transactions data are provided by the MTS Group, the RepoFunds rate is published by the NEX Exchange.

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 $Long_i$ dummy; the amount issued, in billions, $AmtIssue_i$; the volatility of the bond returns, σ_{it}^B ; 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 log, $LogBA_{it}^B$ 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 Specification 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 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, the RepoFunds rate is published by the NEX Exchange.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	BA_{it}^B	BA_{it}^B	BA_{it}^B	BA_{it}^B	$LogBA_{it}^B$	BA_{it}^{Del}	BA_{it}^B
DE_i	-0.044*** (-8.855)	-0.034*** (-3.448)	-0.034*** (-4.615)	-0.033*** (-4.292)	-0.472*** (-5.130)	-0.052*** (-9.315)	-0.003 (-0.568)
$ECB_{it}^{\%}$	0.189*** (3.479)	0.139** (2.271)	0.146** (2.527)	0.188*** (3.038)	2.134** (2.504)	0.164*** (3.584)	0.077* (1.802)
TtM_{it}		0.012 (0.703)	-0.001 (-0.079)	0.001 (0.063)	0.043 (0.330)		-0.002 (-0.268)
$Long_i$		0.009 (1.238)	0.013** (2.094)	0.014** (2.046)	0.126 (1.429)		0.019*** (3.954)
$AmtIssue_i$		0.001 (0.938)	0.000 (0.453)	0.000 (0.283)	0.009 (0.808)		0.000 (0.144)
σ_{it}^B			0.031*** (5.674)	0.031*** (5.878)	0.324*** (6.867)		0.005** (2.110)
$Volume_{it}^B$			-0.102*** (-5.553)	-0.102*** (-5.533)	-1.048*** (-5.923)		-0.075*** (-4.538)
$CCBSS_t$				0.000 (-1.127)	-0.002 (-0.817)		0.000** (-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, $ECB_{it}^{9\%}$. 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 $Long_i$ dummy; the amount issued, in billions, $AmtIssue_i$; the volatility of the bond returns, σ_{it}^B ; and the bond bid-ask spread, BA_{it}^B . We substitute the left-hand side variable with the RepoFunds rate, RFR_{it} , a quantity weighted repo rate index calculated with transactions, both general collateral (GC) and special, involving sovereign government bonds and taking place on the MTS and BrokerTec platforms, and published by the NEX Group. We calculate a 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 Specification 1, 4, and 5, and at the delivery- and day-level for specification 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 and futures data are obtained for the Eurex market via Thomson Reuters. The overnight EONIA and $CCBS_{it}$ rates are obtained from Bloomberg. Repo transactions data are provided by the MTS Group, the RepoFunds rate is published by the NEX Exchange.

	(1)	(2)	(3)	(4)	(5)
	$CTDRepo_{it}$	RFR_{it}	\widehat{RFR}_{it}	$CTDRepo - RFR_{it}$	$CTDRepo - \widehat{RFR}_{it}$
DE_i	-0.108*** (-2.637)	-0.072** (-2.414)	-0.114*** (-3.898)	-0.046 (-1.457)	-0.021 (-0.777)
$ECB_{it}^{9\%}$	-6.759*** (-19.796)	-4.644*** (-15.080)	-5.239*** (-14.682)	-2.107*** (-9.319)	-1.449*** (-5.496)
σ_{it}^B				-0.003 (-0.311)	0.012 (1.100)
$AmtIssue_i$				0.001 (0.145)	0.006 (1.074)
BA_{it}^B				-0.225 (-0.748)	-0.362* (-1.717)
TtM_{it}				-0.019 (-0.515)	-0.018 (-0.578)
$Long_i$				0.008 (0.285)	-0.038 (-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, $ECB_{it}^{c\%}$. 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 $Long_i$ dummy; the amount issued, in billions, $AmtIssue_i$; the volatility of the bond returns, σ_{it}^B ; and the bond bid-ask spread, BA_{it}^B . 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 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, the RepoFunds rate is published by the NEX Exchange.

	(1)	(2)	(3)
	$CTDRepoRange_{it}$	$CTDRepoRange_{it}$	$CTDRepo\sigma_{it}$
DE_i	-0.003 (-0.444)	-0.004 (-0.377)	-0.003 (-0.394)
$ECB_{it}^{c\%}$	0.678*** (5.850)	0.685*** (5.463)	0.563*** (5.935)
σ_{it}^B		-0.002 (-0.346)	-0.007 (-1.464)
$AmtIssue_i$		0.000 (-0.038)	0.000 (0.227)
BA_{it}^B		0.028 (0.174)	0.087 (0.742)
TtM_{it}		0.007 (0.423)	0.015 (1.101)
$Long_i$		-0.005 (-0.408)	-0.017 (-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 Specification 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'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_{it}^B ; 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. Specifications 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. The overnight EONIA and $CCBS_t$ rates are obtained from Bloomberg. Repo transactions data are provided by the MTS Group, the RepoFunds rate is published by the NEX Exchange.

	(1)	(2)	(3)	(4)
	$Basis_{it}$	$Basis_{it}$	$TradeBasis_{it}$	$Arbitrage_{it}$
DE_i	0.036*** (4.935)	0.036*** (5.125)	0.043*** (8.264)	0.027*** (2.894)
$ECB_{it}^{\%}$	0.817*** (10.781)	0.283** (1.996)	0.188*** (5.014)	0.319*** (4.249)
DtD_{it}	0.001*** (4.923)	0.001*** (5.367)	0.001*** (4.669)	0.001*** (3.645)
$CTDRepo_{it}$		-0.070*** (-3.083)		
BA_{it}^B		0.169 (1.311)		
$CTDRepoRange_{it}$		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 Specification 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 a buy the futures contract, $TradeBasis_{it}$. We calculate the profits by using the bond's bid-price and the futures'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_{it}^B ; 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. The overnight EONIA and $CCBSS_t$ rates are obtained from Bloomberg. Repo transactions data are provided by the MTS Group, the RepoFunds rate is published by the NEX Exchange.

	(1)	(2)	(3)	(4)
	$\Delta_{90}Basis_{it}$	$\Delta_{90}Basis_{it}$	$\Delta_{90}TradeBasis_{it}$	$\Delta_{90}Arbitrage_{it}$
DE_i	0.001*	-0.002***	-0.001*	0.002***
	(1.695)	(-3.471)	(-1.752)	(3.888)
ECB_{it}	0.019***	0.006***	0.006***	0.003***
	(10.187)	(3.539)	(3.738)	(4.998)
$\Delta_{90}CTDRepo_{it}$		-0.097***		
		(-11.944)		
$\Delta_{90}BA_{it}^B$		0.147***		
		(4.079)		
$\Delta_{90}CTDRepoRange_{it}$		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 cheapest-to-deliver (% CTD). We report the percentage of physically settled contracts that were settled with the bond we identify as the cheapest-to-deliver (% of Delivered). The data are obtained from Eurex.

Delivery	Bond	Germany		Bond	IT	
		% CTD	% of Delivered		% 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 cohort of macro variables. Variables for Italian bonds are shown in Panel A. The corresponding quantities for German bonds are shown in Panel B. The original sample consists of high frequency bond quotes and transactions and repo transactions for 1,058 bond-days for each of the two countries we analyze and is obtained from the MTS Group. BA_{it}^B is the CTD bond bid-ask spread and σ_{it}^B 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 $Yield_{it}$, the CTD's yield and $Duration_{it}$, its duration. We report the CTD bond characteristics $Maturity_{it}$, its original maturity, TtM_{it} , its time to maturity, and $AmtIssue_{it}$, its amount issued in billions. We calculate $Volume_{it}^B$, 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, $CTDRepoRange_{it}$ ($CTDRepo\sigma_{it}$) 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 European Central Bank as a result of its QE, $ECB_{it}^{\%}$, the RepoFunds rate index, i.e., the average repo rate for a generic repo transaction for that country, RFR_{it} , and our replication of the RepoFunds rate index, \widehat{RFR}_{it} , where we exclude general collateral repo transactions. Data on the ECB purchases were obtained from the website of the ECB, the amounts of sovereign bond outstanding were obtained from the websites of national central banks, and repo rate indexes were obtained from the website of 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 and futures data are obtained for the Eurex market via Thomson Reuters. The overnight EONIA and $CCBS_{it}$ rates are obtained from Bloomberg. Repo transactions data are provided by the MTS Group, the RepoFunds rate is published by the NEX Exchange.

Panel A: Italy							
Variable	Mean	Std	P5	P25	Median	P75	P95
BA_{it}^B	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_{it}^B	1.309	0.533	0.684	0.940	1.179	1.549	2.379
$Volume_{it}^B$	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_{it}^B	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_{it}^B	1.028	0.290	0.673	0.837	0.971	1.150	1.540
$Volume_{it}^B$	0.001	0.006	0.000	0.000	0.000	0.000	0.005
$CTDRepo_{it}$	-0.364	0.440	-1.100	-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 by the ECB of sovereign bonds 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 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 at a quarterly frequency. Data on bond prices and repo rates involved in the arbitrage strategy are obtained from MTS, while data on the futures contracts are obtained from Thomson Reuters. The period of quantitative easing, i.e., when the ECB was actively 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.

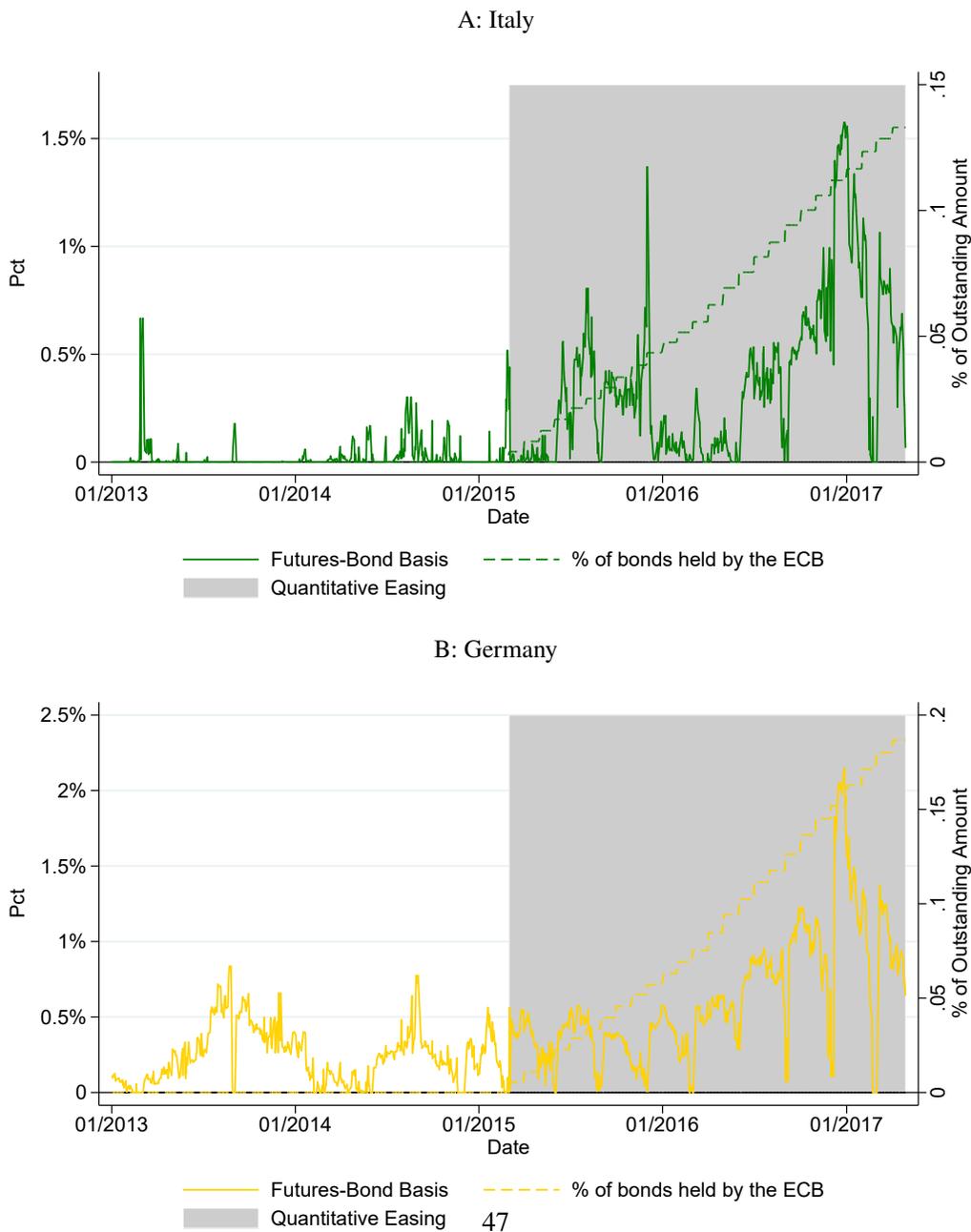
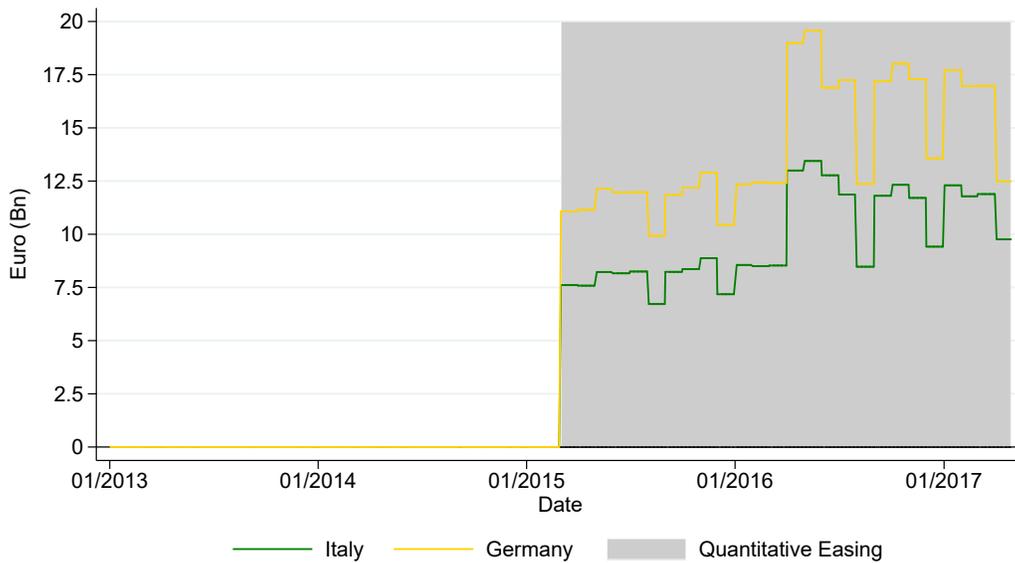


Figure 2
Central Bank Holdings of Italian and German Sovereign Bonds

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 euro, 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 at a quarterly frequency. The period of quantitative easing, 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

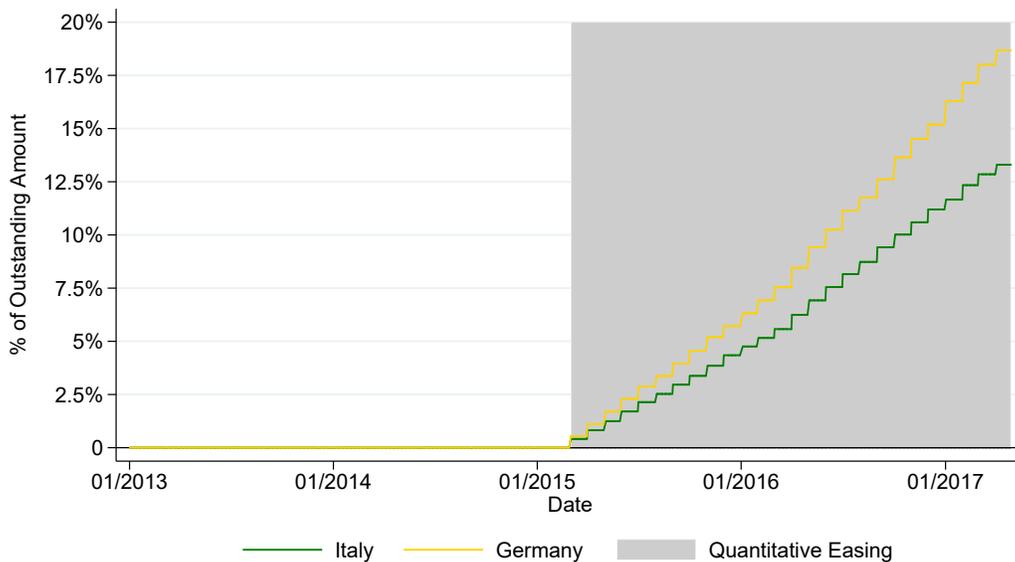


Figure 3
Mispricing between Bonds and Futures

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 mid-quotes 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 period of quantitative easing, 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.

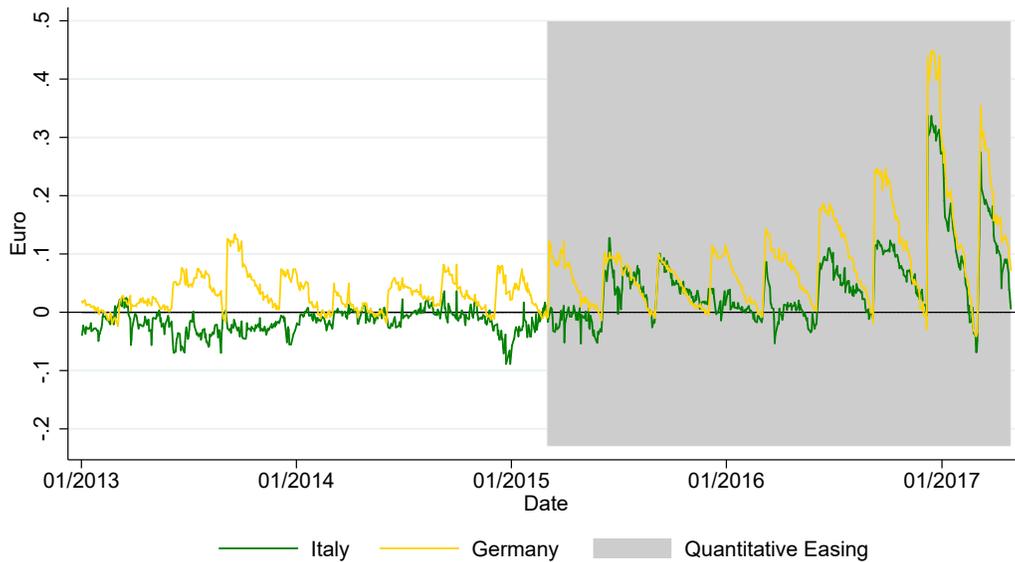


Figure 4
Half-life of a Shock to Bonds or Futures Prices

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, $\Delta Basis_{it} = \alpha Basis_{it-1} + \epsilon_{it}$ 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 period of quantitative easing, i.e., when the ECB was purchasing bonds, is shaded in gray and starts in March 2015.

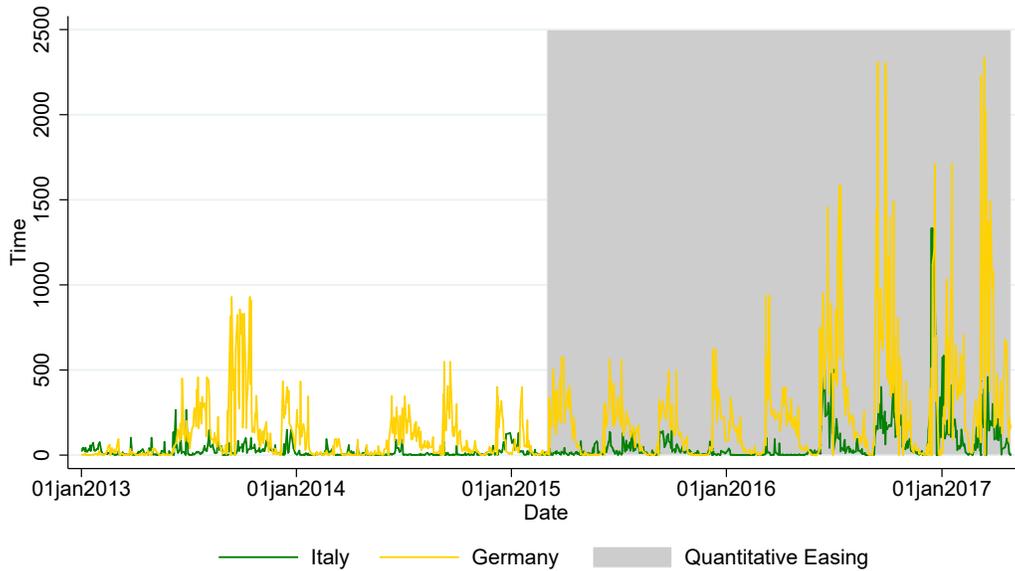


Figure 5
Bond Market Illiquidity

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 period of quantitative easing, i.e., when the ECB was purchasing bonds, is shaded in gray and starts in March 2015. The period of quantitative easing, 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.

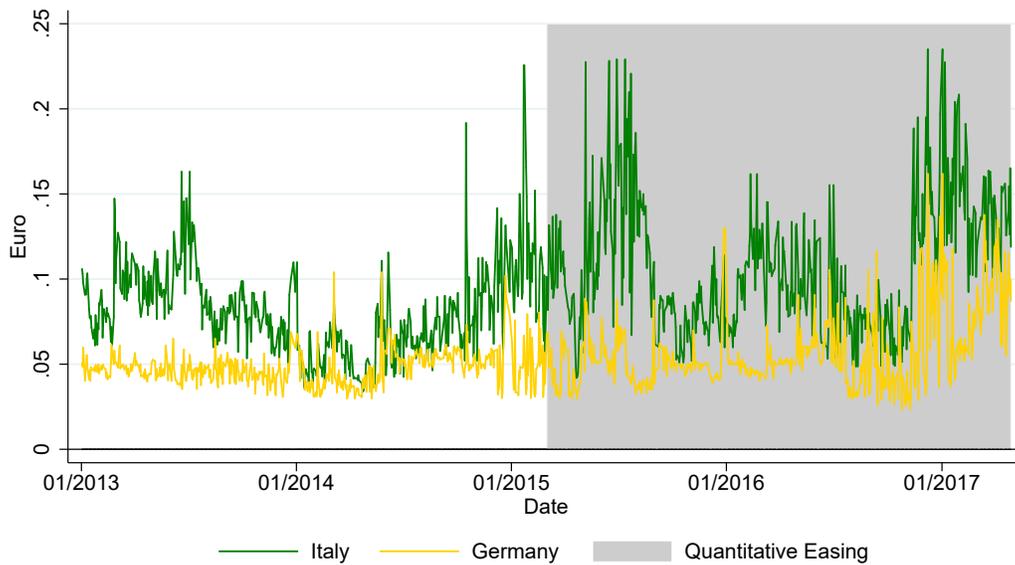


Figure 6
Bond and Index Repo Rates

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 RepoFunds rates, an quantity-weighted index of repo rates for all G.C. 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 period of quantitative easing, i.e., when the ECB was purchasing bonds, is shaded in gray and starts in March 2015.

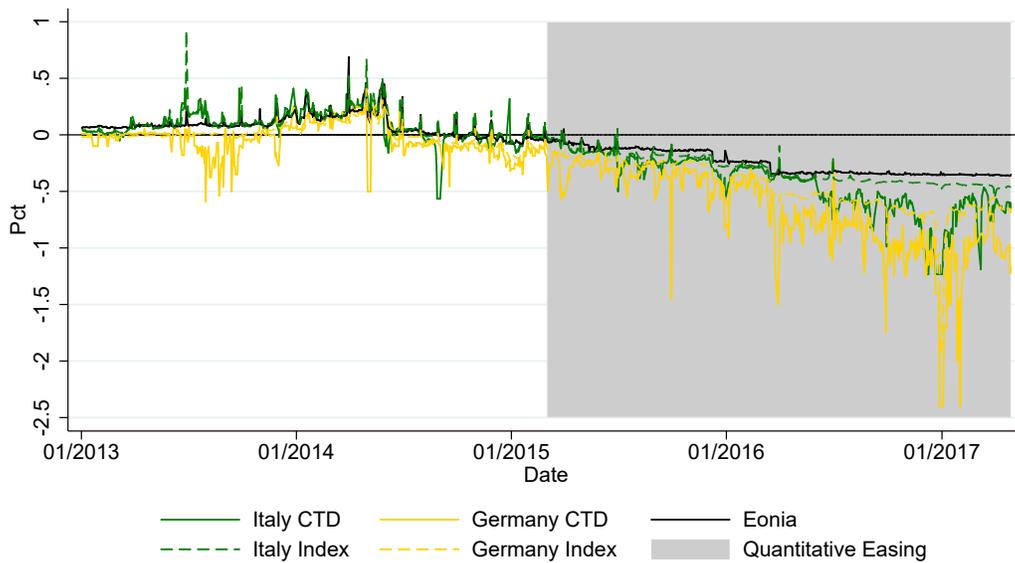


Figure 7
Repo Rate Dispersion

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 period of quantitative easing, i.e., when the ECB was purchasing bonds, is shaded in gray and starts in March 2015.

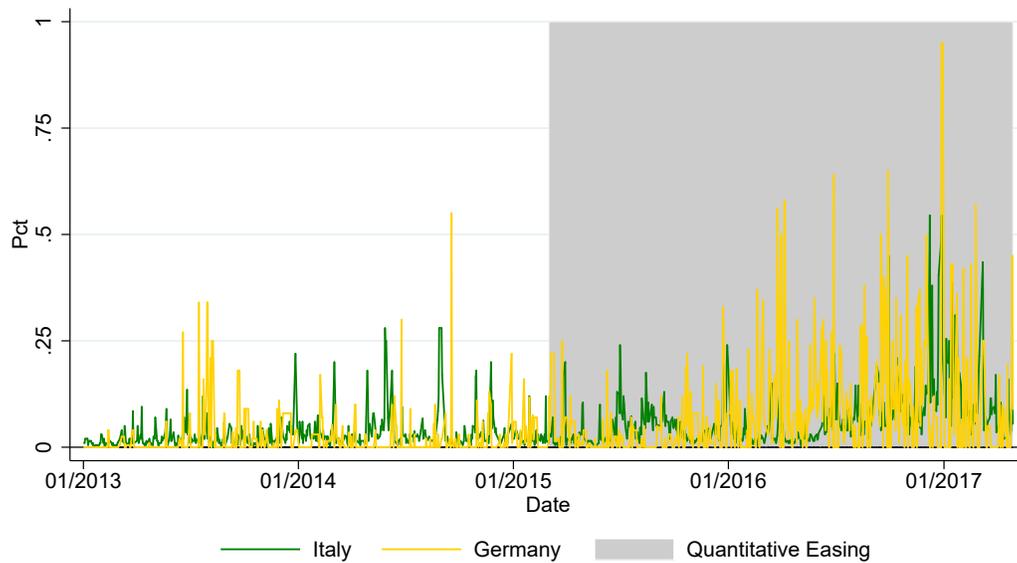
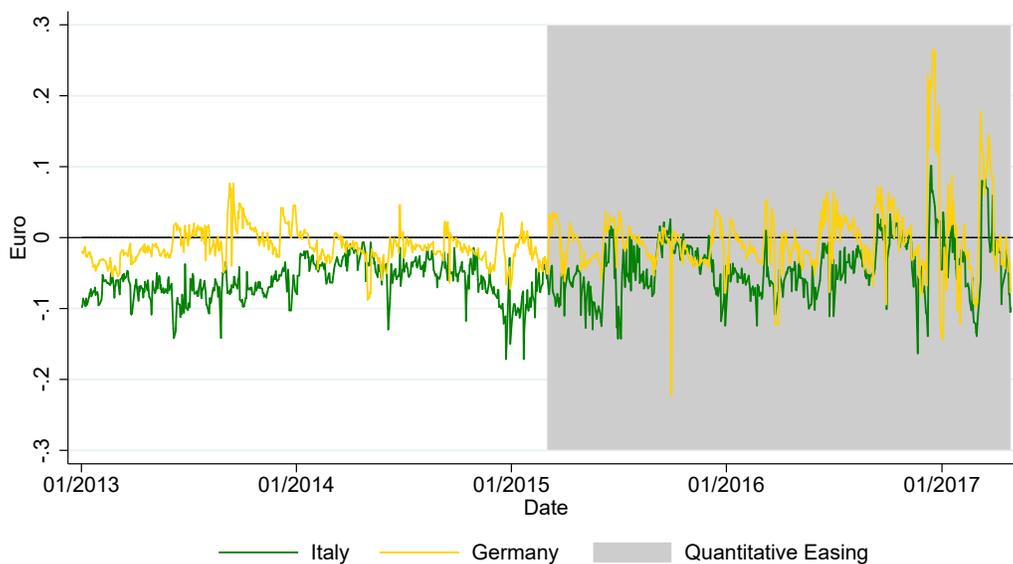


Figure 8
Futures-Bond Arbitrage Opportunities

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), $TradeBasis_{it}$. 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 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 period of quantitative easing, 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. The overnight EONIA and $CCBS_t$ rates are obtained from Bloomberg. Repo transactions data are provided by the MTS Group, the RepoFunds rate is published by the NEX Exchange.

A: $TradeBasis_{it}$



B: $Arbitrage_{it}$

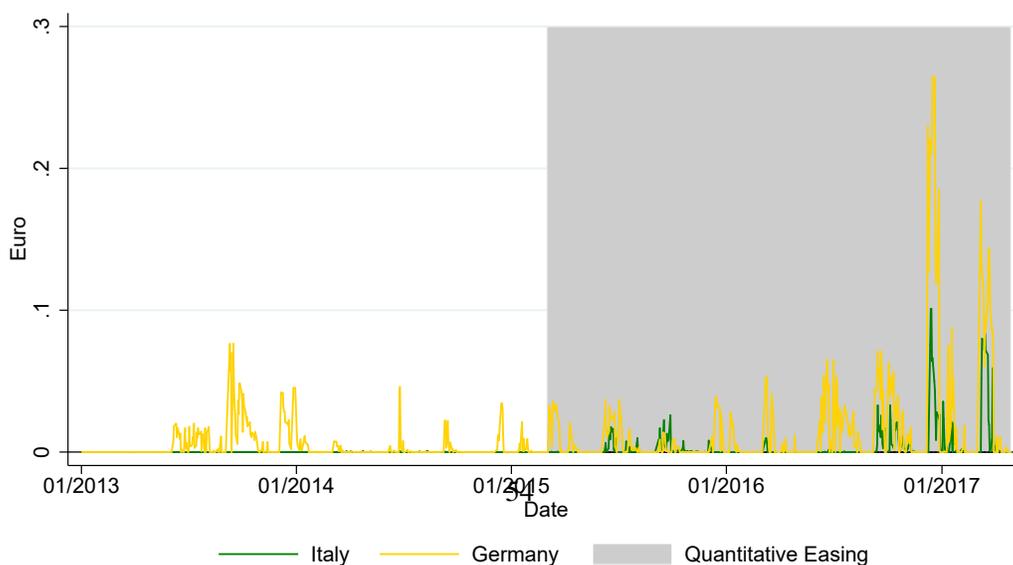


Figure 9
Cheapest-to-Deliver Frequency and Days to Delivery

This figure shows the frequency the bond we identify as CTD has the smallest basis at different times during the life of the futures contract, average across all 17 contracts in our sample. 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 $CCBS_t$ rates are obtained from Bloomberg. Repo transactions data are provided by the MTS Group, the RepoFunds rate is published by the NEX Exchange.

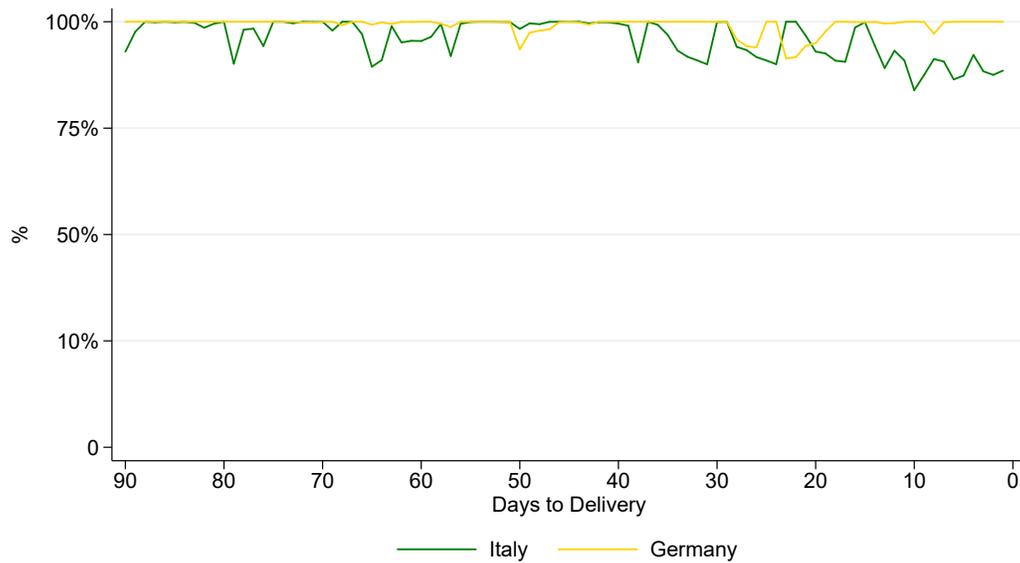


Figure 10
Cheapest-to-Deliver Yield

This figure 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 yield from high-frequency quotes for 1,058 bond-days 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.

