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QE Auctions of Treasury Bonds

Zhaogang Song and Haoxiang Zhu

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Zhaogang Song† Haoxiang Zhu‡

June 16, 2014

Preliminary. Comments welcome

Abstract

The Federal Reserve (Fed) uses a unique auction mechanism to purchase U.S. Treasury securities in implementing its quantitative easing (QE) policy. In this paper, we study the outcomes of QE auctions and participating dealers' bidding behaviors from November 2010 to September 2011, during which the Fed purchased $780 billion Treasury securities. Our data include the transaction prices and quantities of each traded bond in each auction, as well as dealers' identities. We find that: (1) In QE auctions the Fed tends to exclude bonds that are liquid and on special, but among included bonds, purchase volumes gravitate toward more liquid bonds; (2) The auction costs are low on average: the Fed pays around 0.7 cents per $100 par value above the secondary market ask price on auction dates; (3) The heterogeneity of Fed's costs across bonds relates to their liquidity and specialness, suggesting that dealers respond to both valuation and information uncertainties; (4) Dealers exhibit strong heterogeneity in their participation, trading volumes, and profits in QE auctions; (5) Auction bidding variables forecast bond returns only one day after the auction, suggesting that dealers have price-relevant information but the information decays quickly.

Key Words: Auction, Federal Reserve, Quantitative Easing, Specialness, Treasury Bond

JEL classification: G12, G13

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†Board of Governors of the Federal Reserve System, Mail Stop 165, 20th Street and Constitution Avenue, Washington, DC, 20551. E-mail: Zhaogang.Song@frb.gov.

‡MIT Sloan School of Management and NBER, 100 Main Street E62-623, Cambridge, MA 02142. zhuh@mit.edu.

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Abstract

The Federal Reserve (Fed) uses a unique auction mechanism to purchase U.S. Treasury securities in implementing its quantitative easing (QE) policy. In this paper, we study the outcomes of QE auctions and participating dealers' bidding behaviors from November 2010 to September 2011, during which the Fed purchased $780 billion Treasury securities. Our data include the transaction prices and quantities of each traded bond in each auction, as well as dealers' identities. We find that: (1) In QE auctions the Fed tends to exclude bonds that are liquid and on special, but among included bonds, purchase volumes gravitate toward more liquid bonds; (2) The auction costs are low on average: the Fed pays around 0.7 cents per $100 par value above the secondary market ask price on auction dates; (3) The heterogeneity of Fed's costs across bonds relates to their liquidity and specialness, suggesting that dealers respond to both valuation and information uncertainties; (4) Dealers exhibit strong heterogeneity in their participation, trading volumes, and profits in QE auctions; (5) Auction bidding variables forecast bond returns only one day after the auction, suggesting that dealers have price-relevant information but the information decays quickly.

1 Introduction

One of the most dramatic events in the history of the U.S. Treasury market is the Federal Reserve's large-scale asset purchase programs of long-term Treasury securities since the 2008 financial crisis, commonly known as "quantitative easing" (QE).[1] The QE program was introduced in response to the tightening financial and credit conditions during the financial market turmoil, while the federal funds rate—the usual tool of monetary policy—was stuck at the zero lower bound. Through September 2011, the end of the sample period in our study, the Federal Reserve (Fed) purchased $1.19 trillion of Treasury debt. These purchases are equivalent to about 28% of the total outstanding stock of these securities at the beginning of the QE program of Treasury securities in March 2009, and about 15% of the total outstanding stock of these securities in September 2011.

Clearly, shifting such large amounts of Treasury bonds from investors to the Fed requires a well-structured mechanism. The mechanism used by the Fed is QE auctions—a series of multi-object, multi-unit, and discriminatory-price auctions, conducted with primary dealers recognized by the Fed. The principal purpose of this study is to empirically characterize the outcomes of QE auctions and primary dealers' strategic behaviors, guided by auction theory.

An microeconomic understanding of QE auctions is important for a few reasons. First, the sheer size of the Fed's purchase may raise concerns of price-impact costs. Do QE auctions execute the Fed's purchases effectively, at reasonable costs? Second, the analysis of QE auctions sheds light on the strategic behaviors of dealers, who act as key intermediaries between the Fed and investors in U.S. Treasury markets. To what extent do dealers differ in their participation, offers, trading volumes, and profits? What economic channels determine this difference? Third, QE auctions reveal information regarding dealers' bidding strategy *in addition* to the purchase amounts. What information do auction variables contain in forecasting post-auction bond returns and liquidity?

We seek answers to these questions in this study, guided by auction theory of strategic behavior of auction participants. To the best of our knowledge, this paper provides the first analysis of the QE purchase auctions of Treasury securities.[2] Our data includes the 139 purchase auctions of nominal Treasury securities from November 12, 2010, to September 9, 2011, with a total purchased amount of $780 billion (in par value). This amount includes

[1] The large-scale asset purchase programs began with the purchasing of agency mortgage-backed securities and agency debt announced in November 2008. Since our study focuses on purchases of Treasury bonds, we shall use QE for purchase operations of Treasury securities throughout the paper.

[2] A recent paper Pasquariello, Roush, and Vega (2014) studies how the Fed's open market operations in normal times affect the Treasury market microstructure, using only the purchase amount.

the entire purchase of the "QE2" program, $600 billion, as well as the $180 billion reinvestment by the Fed of the principal payments from its agency debt and agency MBS holdings. The distinguishing feature of our study is the use of detailed data of each accepted offer, including dealers' identities, released by the Fed in accordance with the Dodd-Frank Wall Street Reform and Consumer Protection Act (Dodd-Frank Act), passed in July 2010. This allows us to study not only the auction outcomes at the aggregate level, but also the granular heterogeneity of Treasury bonds and primary dealers.[3]

The unique QE auction mechanism and theory

While the objective of the QE program is to provide monetary policy stimulus to the economy, the outright purchase operations need be conducted in a manner that encourages competitive pricing to avoid excessive burdens on U.S. taxpayers (Potter (2013)). However, the Federal Reserve might have been expected to incur significant costs in executing its QE programs given the sheer size of the purchases ($780 billion), conducted in a relatively short time window (around 10 months). In fact, the purchase operations of the $600 billion of the "QE2" program from November 2010 to July 2011 "involve the Federal Reserve purchasing, over an eight-month period, more Treasury securities than the amount currently held by the entire U.S. commercial banking system" (Sack (2011)).

The Fed uses a unique (reverse) auction mechanism to purchase Treasury securities. The auctions are conducted on its FedTrade system and implemented by the Open Market Trading Desk at the Federal Reserve Bank of New York. Specifically, for each purchase operation, the Fed announces a *range* of total amount and a *maturity bucket* of the Treasury bonds to be purchased, but specifies neither the exact total amount nor the amount for individual bonds. Each operation is organized as a multi-object, multi-unit, and discriminatory-price auction, which allows participants to place multiple offers (up to nine on each bond) across all eligible securities simultaneously. Only primary dealers, the trading counterparties recognized by the Federal Reserve Bank of New York, are eligible to participate in the QE auctions directly, but investors can sell securities to the Fed through the primary dealers.

The submitted offers are assessed by the Fed based on a combination of prevailing secondary market prices at the close of the auction and the Fed's internal spline-based prices.[4]

[3]Technically, only Treasury securities with maturities of 20 to 30 years at issuance are Treasury bonds, whereas those with maturities of 2 to 10 years at issuance are Treasury notes. We call them Treasury bonds without making a distinction for convenience.

[4]According to the Federal Reserve Bank of New York, this internal spline-based price is calculated from a spline model fitted through the prices of Treasury securities across CUSIPs (Sack (2011)). The Fed does

The Fed's internal spline prices serve as a benchmark for evaluating the relative attractiveness of offers on different CUSIPs. On the one hand, once these spline-based prices are taken into account, different Treasury bonds (CUSIPs) become perfectly substitutable, and the Fed can take the relatively attractive offers (i.e. with lower prices) among many different eligible bonds. This flexibility should reduce the Fed's purchase costs. On the other hand, this internal spline-based price can also exacerbate the winner's curse problem and induce strategic responses from the primary dealers. Moreover, dealers with sufficient experience in the Treasury market may be able to (approximately) reverse-engineer the Fed's internal spline-based price. These incentives can increase the Fed's purchase cost.

To guide our empirical investigation, we construct a stylized model of QE auctions and characterize dealers' equilibrium bidding strategies. We aim to capture dealers' heterogeneity in two dimensions. First, dealers differ in their valuations for the same Treasury bonds. In our context, valuation heterogeneity is a proxy for heterogeneity in dealers' inventories, risk-bearing capacities, or intermediation activities in Treasury market. Second, some dealers could have better information regarding the Fed's internal spline prices than others. In equilibrium, each dealer offers to sell the bond at its value plus a markup, where the markup depends on the distribution of other dealers' valuations and private information regarding the Fed's internal spline prices. This two-dimensional heterogeneity serves as our guiding principal in conducting the empirical analysis and interpreting our findings.

Eligible Treasury bonds, transaction volumes, and offer dispersion

We first examine the behavior of the Fed as auctioneer. As planned, 86% of the QE purchases concentrate on four maturity buckets: 2.5–4 year, 4–5.5 year, 5.5–7 year, and 7–10 year. The purchase quantities across the four buckets are roughly equal. Only 6% of the total purchased Treasury securities have maturities beyond 10 years, and only 5% of the total purchases happen in the 1.5–2.5 year bucket. Treasury Inflation-Protected Securities (TIPS), which we exclude in our study, account for only 3% of the total purchases.

Within the maturity bucket of each auction, the Fed decides which bonds (CUSIPs) to exclude and communicates this choice to dealers. We find that the Fed tends to exclude liquid bonds with the highest specialness (the specialness of a Treasury bond is the difference between the general repo rate and the special repo rate on that bond), lowest bid-ask spread, and the longest time to maturity. This behavior is consistent with the Fed's communication

not publish their spline-based prices, but market participants can implement a similar method to measure the bond values along the curve.

to the public that it will avoid buying bonds trading on special in repo markets or the cheapest-to-deliver bonds for futures contracts.

Among the included bonds, however, there is strong evidence that transaction volumes gravitate toward more liquid bonds. For example, if one CUSIP has a relative bid-ask spread that is one basis point narrower than that of another, the Fed would on average purchase $130 million more of the first CUSIP than the second. A Treasury security with a $10 billion higher outstanding balance is associated with a $110 million higher purchase amount in QE auctions. If we only consider bonds that are actually purchased (i.e. excluding eligible bonds with a zero purchase amount), the magnitudes become even larger. The higher transaction volume of more liquid bonds could be due to the relative ease dealers have in locating them.

Next, we examine the bidding behavior of primary dealers. We find that the dispersion of dealers' offers on a bond is higher if that bond has a higher bid-ask spread or a lower outstanding balance (suggesting that the bond is less liquid). Interestingly, dealers' offer dispersion is also higher on bonds with a higher specialness (suggesting that the bond is more liquid). These seemingly contrasting patterns, however, are consistent with implications from auction theory that the heterogeneity of offers reflects the heterogeneity of valuations and information. On the one hand, less liquid bonds are harder to value, and the heterogeneity of dealers' valuations about them is higher. On the other hand, a high specialness on a Treasury bond may reflect the fact that dealers find it more difficult to reverse-engineer the Fed's internal spline-based price on this bond, as it falls far away from the spline fitted by the Fed. As a result, the heterogeneity of dealers' information of the Fed's internal spline-based price on (more liquid) bonds with high specialness will be high.

Costs to the Federal Reserve and dealer profitability

An important measure for the effectiveness of QE auctions is their costs. We measure the costs to the Fed by the difference between the accepted offer prices and the secondary market prices of the same bonds at the time the auctions are closed, all weighted by the accepted quantity. Overall, the costs to the Fed appear low. On average, the Fed pays about 0.7 cents per $100 par value more than the ask price in the secondary market. Relative to the mid quotes, the Fed pays 2.1 cents per $100 par value higher. Moreover, the aggregate costs vary substantially across the 139 QE auctions, with the standard deviation of costs to mid quote being 11 cents per $100 par value.

Further, we find that the Fed's costs are heterogeneous among the purchased bonds. The Fed's costs relative to ask prices are higher if the bonds are more special. If benchmarked against the bid quotes or mid quotes in the secondary markets, the Fed's purchase costs are also higher if the bonds are more illiquid, measured by a higher bid-ask spread or a lower outstanding balance. For example, if the bid-ask spread on a bond is one basis point higher, the Fed's cost relative to mid quote is 0.6 cents higher per $100 par value. If the outstanding balance of a bond is $10 billion less, the Fed's cost to the mid quote is 0.76 cents higher per $100 par value. These patterns are consistent with implications of auction theory that dealers respond strategically to the uncertainty regarding bond values or the Fed's internal spline-based prices. As discussed above, high illiquidity may imply high bond value uncertainty faced by dealers, and high specialness may reflect high uncertainty of dealers regarding the Fed's internal spline prices. In consequence, dealers may strategically increase their offer prices, leading to higher costs on illiquid bonds and (liquid) bonds with high specialness.[5]

The flip side of the Fed's cost is the profit of primary dealers. Since the fixed costs of the dealers in providing liquidity are unobservable, we measure dealers' profits as the prices of accepted offers less the secondary market prices (bid, ask, and mid), weighted by accepted quantities. The identities of the dealers in our data enable us to disaggregate the dealers' profits, dealer by dealer. We find a striking dispersion in the profits of primary dealers. Among the 20 primary dealers that participated in QE auctions in our sample period, the top five dealers sold 54% of the $780 billion total Fed purchases. And they account for 96% of all the dealers' profits, if measured against the ask quotes in the secondary market. These fractions are smaller, at 70% and 65%, if the profits are measured against the mid and bid quotes in secondary markets. Their profit margins (dollar profits divided by purchase amounts) are also higher than the average. By contrast, the bottom few dealers sell much smaller amounts of Treasuries to the Fed and make much less profit (in fact a collective loss, if measured against the ask quote).

What contributes to dealers' heterogeneous profits? We find that a dealer's profit margin to the ask quote does not significantly correlate with the characteristics of the bonds the dealer sells. However, if we measure the profit margin relative to the bid or mid quotes, a dealer's profit is higher if he manages to sell bonds that are less liquid, with a lower outstanding balance or a wider bid-ask spread. This pattern is consistent with the evidence above that the Fed's costs on more illiquid bonds are higher, reflecting these dealers' abilities to locate those illiquid bonds.

[5] Alternatively, bonds that are deeply on special or are very illiquid can be difficult for a dealer to source. In this case, the higher purchase costs of the Fed on those bonds may reflect the higher costs incurred by dealers in acquiring them.

Effects of QE auctions on Treasury prices and liquidity

A key objective of the Fed's purchase program is to put a downward pressure on long-term yields, but avoid market dysfunctions in implementing the purchases. The last question we examine is the effect of QE auctions on Treasury prices and liquidity. For this purpose, a pure time-series analysis is hard to interpret because of the confounding effects of other market news and policy initiatives during the crisis. Instead, we run a panel regression of the post-auction bond returns on the purchase amounts and the auction outcomes across CUSIPs.

We find that dealers' bidding behavior, such as offer per dealer, number of dealers, and number of offers, can positively forecast bond returns one day after the auction, but not over longer horizons. This finding suggests that the competitiveness of primary dealers reveals information regarding bond returns, but this information decays quickly. By contrast, purchase amount is only significant over longer horizons. For example, if the purchase amount on a CUSIP is \$1 billion higher than that of another in the same auction, the cumulative return of the first bond is higher than that of the second by about 29 basis points over the next 5 business days. We caution, however, that this magnitude should not be taken literally as we cannot rule out the possibility that certain bonds are bought more by the Fed because they are perceived as "undervalued."

A similar analysis suggests that the Fed's purchase of Treasuries securities does not have any material effect on bond liquidity, measured by bid-ask spread. For example, a \$1 billion higher purchase of a CUSIP is associated with a higher bid-ask spread of 0.05 bps after 5 days. These are much smaller than the average bid-ask spread of 2.4 bps in our sample period.

Related literature

The most directly related paper to our work is Han, Longstaff, and Merrill (2007), who study the Treasury's buyback auctions of long-term debt from March 2000 to April 2002. Our study of QE auctions differs in at least two important aspects. First, though both are discriminatory-price auctions and involve different CUSIPs, QE auctions have an explicitly announced mechanism, whereas the mechanism of the Treasury's buyback auctions is opaque. A transparent and explicit mechanism gives us some guideline to interpret the results. Second, our data include individual accepted offers and dealer identities on each CUSIP in each auction, which are more comprehensive than the CUSIP-level aggregate auction data used by Han, Longstaff, and Merrill (2007). Dealer-level data enable us to look into the heterogeneity of dealers, as suggested by auction theory.

Our analysis of the effect of QE *auctions* on bond prices and liquidity complements the growing literature on the *overall* effects of quantitative easing on interest rates. The vast majority of this literature use event studies, time-series regressions, or term structure models to estimate the effect of QE on interest rates and the relevant channels. Papers taking this approach include Krishnamurthy and Vissing-Jorgensen (2011), Gagnon, Raskin, Remanche, and Sack (2011), Hancock and Passmore (2011), Swanson (2011), Wright (2012), D'Amico, English, Lopez-Salido, and Nelson (2012), Hamilton and Wu (2012), Christensen and Rudebusch (2012), Stroebel and Taylor (2012), Bauer and Rudebusch (2013), and Li and Wei (2013), among others. Another group of studies, such as D'Amico and King (2013) and Meaning and Zhu (2011), estimate the effect of QE through a panel data analysis using CUSIP-level data on Fed purchases.

The objective of our paper is different from that of the QE literature mentioned above. Instead of estimating the overall effect of QE on interest rates, we provide a focused study of the mechanism that implements QE policy. An important distinction between our paper and those mentioned above is that we take into account the explicit auction mechanism by which the Fed purchases the Treasury bonds from private investors. With an explicit auction protocol, we use auction theory to guide our empirical analysis and the interpretation of the results. For example, we investigate the explanatory power of auction variables, which directly depend on the information held by the Fed and primary dealers, for post-auction bond returns and liquidity. Moreover, using primary dealers' identifiers in our dataset, we show that dealers have highly heterogeneous profitability and trading volumes with the Fed. This heterogeneity, in turn, shed lights on the process by which primary dealers intermediate trades between the Fed and the rest of the market. To the best our knowledge, this type of dealer-level results are the first in the literature on quantitative easing. Thus, our paper and the existing literature on QE are complementary.

Our paper is also related to the large literature on Treasury issuance auctions, such as Cammack (1991), Simon (1994), and Nyborg and Sundaresan (1996), who use aggregate auction-level data, and Umlauf (1993), Gordy (1999), Nyborg, Rydqvist, and Sundaresan (2002), Keloharju, Nyborg, and Rydqvist (2005), Hortacsu and McAdams (2010), Kastl (2011), and Hortacsu and Kastl (2012), who use bid-level data.[6] QE auctions differ in that each auction involves multiple substitutable CUSIPs, whereas each issuance auction has a

[6] Theoretical and experimental studies of Treasury issuance auctions include Bikhchandani and Huang (1989), Chatterjee and Jarrow (1998), Goswami, Noe, and Rebello (1996), and Kremer and Nyborg (2004), among others.

single CUSIP at a time. Moreover, our data include dealer identities on each CUSIP in each auction, allowing us to study the heterogeneity of dealers' equilibrium bidding strategies and profitability in a panel data analysis. Studies of issuance auctions either do not have dealer identities or only have masked identifiers.

2 Institutional Background

From November 12, 2010, to September 9, 2011, the Federal Reserve conducted a series of 156 purchase auctions of U.S. Treasury securities, including Treasury notes, bonds, and Inflation-Protected Securities (TIPS). These auctions cover two Fed programs. The first, so-called QE2, is the $600 billion purchase program of Treasury securities, announced on November 3, 2010, and finished on July 11, 2011. The second program is the reinvestment of principal payments from agency debt and agency MBS into longer-term Treasury securities, announced on August 10, 2010, with a total purchase size of $180 billion over our sample period.[7] (We discuss our data and sample period shortly.) These actions are expected to maintain downward pressure on longer-term interest rates, support mortgage markets, and help to make broader financial conditions more accommodative, as communicated by the Federal Open Market Committee (FOMC).

The QE auctions are designed as a series of sealed-offer, multi-object, multi-unit, and discriminatory-price auctions. Transactions are conducted on the FedTrade platform. Direct participants of QE auctions only include the primary dealers recognized by the Federal Reserve Bank of New York, although other investors can indirectly participate through the primary dealers. In the first half of our sample period until February, 2, 2011, there are 18 primary dealers, including BNP Paribas Securities Corp (BNP Paribas), Bank of America Securities LLC (BOA), Barclays Capital Inc (Barclays Capital), Cantor Fitzgerald & Co (Cantor Fitzgerald), Citigroup Global Markets Inc (Citigroup), Credit Suisse Securities USA LLC (Credit Suisse), Daiwa Securities America Inc (Daiwa), Deutsche Bank Securities Inc (Deutsche Bank), Goldman Sachs & Co (Goldman Sachs), HSBC Securities USA Inc (HSBC), Jefferies & Company, Inc (Jefferies), J. P. Morgan Securities Inc (J. P. Morgan), Mizuho Securities USA Inc (Mizuho), Morgan Stanley & Co. Incorporated (Morgan Stanley), Nomura Securities International, Inc (Nomura), RBC Capital Markets Corporation (RBC), RBS Securities Inc (RBS), and UBS Securities LLC (UBS). On February 2, 2011, MF Global

[7] Principal payments from maturing Treasury securities are also invested into purchases of Treasury securities in auctions.

Inc (MF Global) and SG Americas Securities, LLC (SG Americas) were added to the list of primary dealers, making the total number of primary dealers 20 in the second half our sample period.[8]

Figure 1 describes the timeline of QE auctions, including pre-auction announcement, auction execution, and post-auction information release. To initiate the asset purchase operation, the Fed publishes a pre-auction announcement on or around the eighth business day of each month. The announcement includes an anticipated total amount of purchases expected to take place between the middle of the current month and the middle of the following month.[9] Most importantly, this announcement also includes a schedule of anticipated Treasury purchase operations, including operation dates, settlement dates, security types to be purchased (nominal coupons or TIPS), the maturity date range of eligible issues, and an expected range for the size of each operation. Therefore, the announcement identified the set of eligible bonds to be included as well as the minimum and maximum total notional amount (across all bonds) to be purchased in each planned auction. While the purchase amount has to reach the minimum expected size, the Fed reserves the option to purchase less than the maximum expected size.

[Figure 1 about here.]

On the auction date, each dealer submits up to nine offers per security or CUSIP, with both the minimum offer size and the minimum increment as $1 million. Each offer consists of a price-quantity pair, specifying the par value the dealer is willing to sell to the Fed at a specific price. The auctions happen mostly between 10:15am to 11:00am Eastern Time. Occasionally, the auctions happen between 10:40am and 11:30am, 11:25am and 12:05pm, and 1:15pm and 2:00pm.

In a discriminatory-price auction, offers are either accepted or rejected at the specified prices, and for each accepted offer, the dealer sells its offering amount of bonds to the Fed at its offer price. Since each auction involves a set of heterogeneous securities/CUSIPs, an algorithm is needed to compare the relative attractiveness of offers on different CUSIPs. To make this comparison, the Fed announces that it will compare each offer with a combination of the secondary market prices of similar securities at the close of the auction and its internal

[8]See the website of the Federal Reserve Bank of New York for the historical list of primary dealers.

[9]This amount is determined by the part of the $600 billion purchases that are planned to be completed over the coming monthly period, and the sum of the approximate amount of principal payments from agency MBS expected to be received over the monthly period, and the amount of agency debt maturing between the seventh business day of the current month and the sixth business day of the following month. All the purchases are conducted as one consolidated purchase program.

spline-based prices (Sack (2011)). Thus, the combination of secondary market prices and the Fed's internal spline-based prices makes different CUSIPs essentially perfect substitutes from the Fed's perspective. From the dealers' perspectives, however, information regarding the Fed's internal spline-based prices is valuable for their strategic bidding across different CUSIPs. To the extent that the internal spline-based prices of the Fed also influence the Fed's open market operations and other policy initiatives, these prices can also contain valuable information regarding the returns of different CUSIPs.

Within a few minutes after the closing of the auction, the Fed announces the auction results publicly on the Federal Reserve Bank of New York website, including the total number of offers received, total number of offers accepted, and the amount purchased per CUSIP. At the same time, participating dealers receive their accepted offers via FedTrade. At the end of each scheduled monthly period, coinciding with the release of the next period's schedule, the Fed publishes certain auction pricing information. The pricing information released includes the weighted-average accepted price, the highest accepted price, and the proportion accepted of each offer submitted at the highest accepted price, for each security purchased in each auction. Finally, in accordance with the Dodd-Frank Act, detailed auction results including the offer price, quantity, and dealer identity for each accepted individual offer will be released two years after each quarterly auction period.

3 Implications of Auction Theory for QE Auctions

QE auctions are multiple-object, multiple-unit and discriminatory-price auctions. To the best of our knowledge, this unique combination of institutional features is not yet addressed in existing auction models. In fact, even for a single-object, multiple-unit auction, multiple Bayesian-Nash equilibria can exist, so that no definitive theoretical predictions can be made about the equilibrium bidding strategies and auction outcomes (see, for example, Bikhchandani and Huang (1993); Back and Zender (1993); Ausubel, Cramton, Pycia, Rostek, and Weretka (2013)). The complications of multiple objects and internal spline-based prices involved in QE auctions make a thorough theoretical treatment of QE auctions much more challenging.

Instead of pursuing a full-fledged theory, which is beyond the empirical focus of this paper, we characterize equilibrium strategies of a substantially simplified model in this section. The model we present at this stage is not solved explicitly in closed form, so directional predictions are not obtained. Nonetheless, this model is still useful in highlighting the strategic considerations of dealers participating in QE auctions; it also helps to guide our empirical explorations and the interpretation of the data. This approach is also employed in empirical studies of Treasury issuance auctions, such as Cammack (1991), Umlauf (1993), Gordy (1999), and Keloharju, Nyborg, and Rydqvist (2005).

A stylized model. There are N dealers selling a single indivisible bond to the Fed. The indivisibility assumption is not far-fetched for discriminatory-price auctions. Back and Zender (1993) and Ausubel, Cramton, Pycia, Rostek, and Weretka (2013) show that, in discriminatory-price auctions of divisible assets and under natural conditions, it is an equilibrium for each bidder to bid as if he were in an auction of indivisible assets.[10]

Dealers have private values $\{v_i\}$ for owning the bonds, where $\{v_i\}$ are i.i.d. with distribution function $F : [\underline{v}, \bar{v}] \to [0, 1]$ and density f. The Fed's value, or "reserve price," v_0, has the distribution $G : [\underline{v}, \bar{v}] \to [0, 1]$, with the density g. The Fed is willing to buy the bond as long as the lowest offer is lower than v_0. The difference in valuations among dealers can reflect the heterogeneous hedging needs and customer demands. For example, if a dealer has bought a large bond inventory from its clients in anticipation of selling those bonds to the Fed, this deal may have a low value for holding these bonds. The Fed assigns a potentially different value on the bond because its objective as a central bank can be distinct from that of the dealers. We emphasize that by "independence" of values, we mean conditional independence, where the conditional information is the information available to the dealers prior to the auction date (e.g. prices of interdealer trades). Moreover, although this model does not explicitly have multiple bonds, we interpret the distribution functions F and G as proxies for bond characteristics. For example, if a bond is less liquid, we expect its value distribution F and G to have a higher variance.

Lastly, dealers have heterogeneous information about the Fed's reserve price v_0. For example, some dealers may trade more with the Fed and learn the Fed's valuation methods better than other dealers. In particular, among the N dealers, dealers $1, 2, ..., M$ perfectly observe v_0, whereas dealers $M + 1, ..., N$ do not observe v_0 at all. We refer to the first group as informed dealers, and the second group as uninformed dealers. Clearly, this informed-uninformed dichotomy is a simplification, but it captures the qualitative effect we want to model.

[10]In discriminatory-price auctions, bidders pay their bids on each unit of the asset, regardless of the prices on other units. Therefore, bidders have little incentive to "shade" (i.e. reduce) the bid. By contrast, in divisible auctions with uniform prices, bidders have strong incentives to lower their their bid to make the prices on all units more favorable. This latter incentive is analyzed by Wilson (1979), Back and Zender (1993), and Ausubel, Cramton, Pycia, Rostek, and Weretka (2013), among others.

We conjecture that the informed group of dealers uses a symmetric, v_0-dependent strategy $\{\beta_{v_0} : v \mapsto \beta_{v_0}(v)\}$, whereas the uninformed group of dealers uses a symmetric strategy $\gamma : v \mapsto \gamma(v)$. We also conjecture that the strategies β and γ are strictly increasing and differentiable. The objective is to characterize these strategies.

Strategies of informed dealers. We consider the informed group first. Clearly, no informed dealer would put an ask price higher than v_0, as that price would be rejected for sure. Thus, it is without loss of generality to restrict attention to dealers whose values are no higher than v_0. Also, for notational simplicity, we write β instead of β_{v_0}, as v_0 is known to the informed dealers.

Conditional on the offer $a_i \leq v_0$, dealer i wins if and only if $a_i < \max_{j \neq i} a_j$. Because, by the conjecture, each informed dealer j bids $\beta(v_j)$ and each uninformed dealer m bids $\gamma(v_m)$, dealer i wins if and only if $v_j > \beta^{-1}(a_i)$ for all $j \in \{1, 2, ..., M\} - \{i\}$ and $v_m > \gamma^{-1}(a_i)$ for all $m \in \{M+1, ..., N\}$. The expected profit of dealer i is then

$$\Pi_i^I = (a_i - v_i)[1 - F(\beta^{-1}(a_i))]^{M-1}[1 - F(\gamma^{-1}(a_i))]^{N-M}, \quad v_i \leq a_i \leq v_0. \tag{1}$$

Observe that $\beta(v_0) = v_0$ because any higher ask price will be rejected, and any lower price price will incur a loss. Thus, the objective function Π_i^I is zero at $a_i = v_i$ and $a_i = v_0$.

Strategies of uninformed dealers. The strategies of the uninformed dealers must take into account the uncertainty of the Fed's value v_0. Recall that β_{v_0} is informed traders' strategy conditional on the Fed's value being v_0. A given ask price a_i from uninformed dealers is accepted if and only if: (i) it is lower than other uninformed dealers' ask prices, (ii) it is lower than the Fed reservation price v_0, and (iii) it is lower than the informed dealers' ask prices. Thus, dealer i in the uninformed group has the expected profit of

$$\Pi_i^U = (a_i - v_i)[1 - F(\gamma^{-1}(a_i))]^{N-M-1} \int_{a_i}^{\bar{v}} [1 - F(\beta_{v_0}^{-1}(a_i))]^M g(v_0) dv_0. \tag{2}$$

Characterization of equilibrium strategies. Under certain technical conditions, we can show that the optimal bidding strategies $\{\beta_{v_0}\}$ and γ can be written as solutions to a system of integral equations. We formally state it below.

Proposition 1. *If the distributions F and G are such that the profit functions,* (1) *and* (2)*, are concave in a_i, then the optimal strategies $\{\beta_{v_0}\}$ and γ are characterized by the following* *system of integral equations:*

$$\beta_{v_0}(v) = v + \frac{\int_{u=v}^{v_0}[1-F(u)]^{M-1}[1-F(\gamma^{-1}(\beta_{v_0}(u)))]^{N-M}du}{[1-F(v)]^{M-1}[1-F(\gamma^{-1}(\beta_{v_0}(v)))]^{N-M}}, \quad v \in [\underline{v}, v_0], \tag{3}$$

$$\gamma(v) = v + \frac{\int_{u=v}^{\bar{v}} X(u)du}{X(v)}, \quad v \in [\underline{v}, \bar{v}], \tag{4}$$

where

$$X(v) = [1-F(v)]^{N-M-1}\int_{\gamma(v)}^{\bar{v}}[1-F(\beta_{v_0}^{-1}(\gamma(v)))]^M g(v_0)dv_0. \tag{5}$$

Proof. See the Appendix. □

In equilibrium, informed dealers' strategies depend on v_0, whereas uninformed dealers' strategies depend on the probability density g of v_0. Each dealer offers to sell the bond at its value plus a markup. The heterogeneity in offers reflect dealers' heterogeneity in their valuations or information.

4 Data and Summary Statistics

4.1 Data

Our sample period is from November 12, 2010, to September 9, 2011. We focus on this sample period because of data availability and the impact of monetary policy developments on the timeline of auctions. The Dodd-Frank Act, passed on July 21, 2010, by the U.S. Congress, mandates that the Federal Reserve should release detailed auction data to the public, but with a two-year delay after each quarterly operation period. As of January 2014, detailed data of dealer offers are only available from July 22, 2010 to December 31, 2011. We discard the period July 22, 2010–November 11, 2010, because no expected purchase sizes at the CUSIP level were announced by the Fed in this period. We also discard the period September 10, 2011–December 31, 2011, because the Fed announced its new policies on September 21, 2011, including the Maturity Extension Program and changes in the agency debt and agency MBS reinvestment policy. Thus, in our sample period, the Fed purchased only Treasury securities for its QE policy.

We focus on 139 auctions of nominal Treasury securities among the 156 purchase auctions between November 12, 2010, and September 9, 2011. The excluded 17 auctions of TIPS only account for 3% of the total purchases. Moreover, focusing on auctions of nominal bonds makes the bond characteristics, such as coupon rates and returns, comparable across CUSIPs. These 139 auctions were conducted on 136 days, with two auctions on November 29, 2010, December 20, 2010, and June 20, 2011, and only one auction on all the other days.

Our empirical analysis combines the auction data released by the Federal Reserve and three CUSIP-level data sets of Treasury securities, including the secondary market intraday price quotes, the specific collateral repo rates, and the outstanding quantity. The auction data include: (1) the expected total purchase size range, the total par amount offered, and the total par amount accepted for each auction; (2) the indicator of whether a CUSIP was included or excluded, the par amount accepted, the weighted average accepted price, and the least favorable accepted price for each CUSIP in each auction; and (3) the offered par amount, offer (clean) price, and dealer identity for each accepted offer on each CUSIP in each auction.

To the best of our knowledge, the individual-offer data we use is the first set of auction data at the individual bid level that has been ever analyzed for U.S. Treasury securities. Previous studies of issuance auctions and buyback auctions of U.S. Treasury securities, including Cammack (1991), Simon (1994), Nyborg and Sundaresan (1996), and Han, Longstaff, and Merrill (2007), have used data only at the aggregate auction level or at the CUSIP level at best.[11]

Our secondary market price data contain indicative bid and ask quotes from the New Price Quote System (NPQS) by the Federal Reserve Bank of New York, as well as the corresponding coupon rate, original maturity at issuance, and remaining maturity, which are also used by D'Amico and King (2013). We choose the NPQS quotes because the these data cover off-the-run securities that are mainly involved in QE auctions. (The BrokerTec data used in recent studies such as Fleming and Mizrach (2009) and Engle, Fleming, Ghysels, and Nguyen (2012) mainly contain prices of mostly on-the-run securities.) The NPQS data have four pairs of bid and ask quotes each day, which are the best bid and ask prices across different trading platforms of Treasury securities made at 8:40am, 11:30am, 2:15pm, and 3:30pm. Since the auction close time is one of 11:00am, 11:30am, 12:05pm, and 2:00pm, we use the 11:30am NPQS quotes for the first three auction closing times and the 2:15pm NPQS quotes for the last auction closing time when comparing the auction price with secondary market price. A daily when-issued-count number is also included to signal whether the security is on-the-run or off-the-run, and how off-the-run it is: the number is 0 if the security

[11] Studies of Treasury auctions in other countries have used bid-level data, such as Umlauf (1993), Gordy (1999), Nyborg, Rydqvist, and Sundaresan (2002), Keloharju, Nyborg, and Rydqvist (2005), Hortacsu and McAdams (2010), Kastl (2011), and Hortacsu and Kastl (2012).

is on-the-run, and 1 is added each time a security with the same original maturity and coupon rate is issued.

We obtain the CUSIP-level special collateral repo rates from the BrokerTec Interdealer Market Data that averages quoted repo rates across different platforms between 7am and 10am each day (when most of the repo trades take place). We then calculate the CUSIP-level repo specialness as the difference between the General Collateral (GC) repo rate and specific collateral repo rate, measured in percentage points. This specialness measure reflects the value of a specific Treasury security used as a collateral for borrowing (see Duffie (1996); Jordan and Jordan (1997); Krishnamurthy (2002); Vayanos and Weill (2008)). We also obtain the outstanding par amount of Treasury securities each day from the Monthly Statement of the Public Debt (MSPD) of the Treasury Department.

4.2 Descriptive statistics of QE auctions

Figure 2 presents descriptive statistics on the number of bonds and auction size for these 139 QE auctions (of nominal Treasury securities). The top left panel shows that the number of eligible bonds in an auction varies between 15 and 36, with a mean of 26. On average, one CUSIP is excluded in each auction, with the minimum and maximum number of excluded CUSIPs being 0 and 4, respectively. This leaves the number of eligible (included) bonds between 13 and 34, averaging 25 per auction, as presented in the top right panel. Among these included bonds, 14 (11) bonds were (not) purchased by the Fed on average in each auction, with the minimum and maximum number of bonds purchased (not purchased) being 2 (0) and 26 (28), respectively. Across all 139 auctions, only 186 CUSIPs have ever been purchased by the Fed, among the 215 included CUSIPs.

[Figure 2 about here.]

The bottom left panel shows that the (par) amount of submitted offers varies between \$4 and \$43 billion, averaging \$21 billion per auction, while the amount of offers accepted by the Fed varies between \$0.7 and \$8.9 billion, averaging \$5.6 billion per auction. The ratio between submitted and accepted offer amounts was on average 4.2. In addition, from the bottom right panel, the accepted offers always have a par value that falls between the expected minimum and maximum purchase sizes.

[Figure 3 about here.]

Figure 3 presents descriptive statistics on the number of accepted offers and winning dealers. From the left panels, the number of accepted offers ranges between 8 and 326, with a mean of 103, whereas the number of winning dealers ranges between 4 and 20, with a mean of 16, out of 20 (or 18 before February 2, 2011) primary dealers. From the right panels, the number of accepted offers per CUSIP purchased by the Fed is 8 on average, with a range of 1 to 32, while the number of winning dealers per CUSIP purchased by Fed is 1.3 on average, with a range of 0.4 to 8.5.

What Treasury securities does the Fed (not) buy and what is the allocation of purchasing quantities across different securities? Table 1 reports the maturity distribution of planned purchases in QE Auctions of Treasury debt over our sample period, announced on November 3, 2010, by the Fed. Only 6% of planned purchase amounts have a maturity beyond 10 years. According to the Fed, this maturity distribution is to have an average duration of between 5 and 6 years for the securities purchased.[12]

[Table 1 about here.]

4.3 Key variables for subsequent analysis

Our subsequent analysis focuses on the cross section of bonds and (to a lesser extent) dealers. We will use eight bond characteristics as potential explanatory variables: specialness, outstanding balance, bid-ask spread, coupon rate, on/off-the-run count (on/off count), time to maturity, original maturity at issuance, and volatility. Throughout, we use i to denote an auction and j to denote a CUSIP. Coupon and original maturity depend only on CUSIP j, whereas the other five variables vary with CUSIP j and auction i. Specialness is measured in percentage points. Outstanding balance is the total outstanding par amount of the bond, in 10 billions of dollars. Bid-ask spread is the difference between the ask and bid quotes of a bond, normalized by the mid-quote, denoted in basis points. Since the auction close time is one of 11:00am, 11:30am, 12:05pm, and 2:00pm, we use the 11:30am NPQS quotes for the first three close times and 2:15pm NPQS quotes for the last. Coupon is in percentage points. On/off count of a bond is the cumulative number of new issuance of bonds with the same coupon rate and original maturity. Time to maturity and original maturity are both measured in years. Volatility of a CUSIP is measured by the standard deviation of bond mid-quote returns during the five trading days prior to the auction date.

[12]The Fed does not purchase Treasury bills, STRIPS, or securities trading in the when-issued market. See http://www.newyorkfed.org/markets/lttreas_faq_101103.html for details.

[Table 2 about here.]

Table 2 reports the correlations of these variables across CUSIP/Auction. Panel A reports the correlations by pooling the observations across CUSIP/Auction, while Panel B reports correlations by first computing the correlation matrix across CUSIPs for each auction and then taking averages across auctions in order to control for the effect of panel data. In Panel A, only specialness has a consistently weak correlation with other bond characteristics. Outstanding balance, bid-ask spread spread, coupon rate, on/off count, and original maturity are highly correlated with each other. The average auction-level correlations, shown in panel B, exhibit a similar pattern of high correlation among some bond characteristics. Because of potential multicellularity concerns, in our empirical strategies we will run multiple univariate regressions, instead of multi-variate regressions.

5 Behavior of Auction Participants

In this section, we analyze the behavior of the Fed as auctioneer and the bidding behaviors of primary dealers throughout the QE auction process. More specifically, we study the Fed's decision to include or exclude certain CUSIPs in the auctions, the transaction volumes, and the dispersion of dealers' offers. We relate these three quantities to bond characteristics. The prices of dealers' offers, as well as associated costs to the Fed, are covered in Section 6.

5.1 The decision to include or exclude bonds

As presented earlier, on average, one CUSIP is excluded out of 26 eligible bonds in each auction. According to Fed communications to the public, excluded bonds are those trading with heightened specialness in the repo market, or cheapest to deliver into the front-month Treasury futures contracts.[13] Presumably, the reason for excluding these bonds is to avoid exacerbating supply shortages in repo and futures markets. To formally explore the Fed's decision to include or exclude certain CUSIPs, we estimate a panel logit regression in which the dependent variable, indexed by auction i and CUSIP j, takes the value of one if the jth

[13]The Fed also excludes CUSIPs by the size limit for purchase amount per security according to the percentage of the outstanding issuance and the Fed's existing holdings of this security. See the website of Federal Reserve Bank of New York for details (http://www.newyorkfed.org/markets/lttreas_faq_101103.html). We do not study this criterion as the Fed purchase rarely hit the size limit in our sample. In addition, communications with the Fed confirm that primary dealers have almost perfect foresight about which securities will be excluded before the auction.

CUSIP is included in the ith auction, and zero otherwise. Although the set of CUSIPs varies with the auction number i, we suppress the dependence of j on i for notation simplicity.

[Table 3 about here.]

Table 3 reports the results from the panel Logit regression, controlling for auction fixed effects. As many bond characteristic variables are correlated, we run multiple univariate regressions including one explanatory variable at a time to avoid the multi-collinearity problem. We observe from Table 3 that the regression coefficient of specialness is significantly negative, confirming that the Fed did exclude bonds trading at heightened specialness. Moreover, illiquid bonds with higher bid-ask spreads are more likely to be included, implying that the Fed may also try to improve the market liquidity for relatively illiquid bonds. Finally, the Fed also tends to include bonds with shorter time to maturity, consistent with the pattern shown in Table 1.

5.2 Auction outcomes: volumes and offer dispersion

Now we turn to the analysis of auction outcomes, after the Fed determines the set of included bonds. We emphasize that because the Fed's internal spline prices on various CUSIPs are unobservable to us, the auction outcomes necessarily reflect both the primary dealers' propensity to sell particular bonds and the Fed's propensity to buy them.[14]

Purchase amounts and bond characteristics. We run a panel regression of the par amount accepted, in billions of dollars, for each bond included in an auction on a number of explanatory variables.

The panel "Purchase Amount (Included Bonds)" of Table 4 reports the results from the panel regressions for all included bonds (with both zero and positive purchase amounts), controlling for auction fixed effects. As before, we run multiple univariate panel regressions (to prevent the multi-collinearity problem). Robust t-statistics that correct for serial correlation in the residuals clustered at the auction level are reported in parentheses.

As shown in Table 4, the five variables that are highly significant all suggest that the Fed and the dealers have a combined preference of transacting more liquid bonds. For

[14] To better separate the behaviors of the dealers from that of the Fed, one would need to observe the entire supply curves of dealers on each CUSIP, including both accepted and rejected offers. Comparing the just-accepted offers and just-rejected offers would give us valuable information regarding the Fed's internal spline price across CUSIPs. Unfortunately, such detailed data are unavailable.

example, the Fed has purchased more bonds with a higher outstanding balance, a narrower bid-ask spread, and a lower on/off count. Original maturity and coupon rates are pure bond characteristics that are invariant of time, but in our sample they are highly correlated with bid-ask spread, a measure of illiquidity (see Table 2). The economic magnitudes are also large. If the bid-ask spread of a bond is 1 basis point wider than that of another, the Fed's purchase of the first bond is on average $130 million less than that of the second bond. If a bond has an outstanding balance that is $10 billion larger than another, the Fed's purchase of the first bond is on average $110 million higher than that of the second. Overall, though the Fed tends to exclude the most liquid bonds in its purchase operations, among the included bonds the Fed's purchases tilt toward more liquid ones.

To check that these results are not driven entirely by bonds with zero purchase amounts, we repeat the regressions only for bonds that have strictly positive purchased amounts. The results, reported in the panel "Purchase Amount (Purchased Bonds)" of Table 4, confirm that the Fed and dealers have a combined preference of trading more liquid bonds or bonds with lower transaction costs. The bond characteristics are still statistically significant, and their economic magnitudes also become larger. For example, a one basis point wider spread implies a smaller Fed purchase by $190 million, whereas a $10 billion higher outstanding balance implies a larger Fed purchase by $160 million. The coefficient on specialness also becomes significantly positive and economically large. A 10 basis points increase in repo specialness on a CUSIP is associated with an increase in Fed purchase of $253 million on that CUSIP.

[Table 4 about here.]

Offer dispersions and bond characteristics. Now, we turn to the relation between offer dispersions and bond characteristics. This exercise is useful because, as auction theory suggests, the dispersion of offers is an indication of heterogeneous valuations or information among dealers.

Specifically, suppose that the oth winning offer price and par amount of dealer d for CUSIP j in auction i are $p_{i,j,d,o}$ and $q_{i,j,d,o}$, respectively. Then we define the Offer Dispersion for the CUSIP j of auction i as

$$\text{Offer Dispersion} = \frac{\sum_{d,o} \left(p_{i,j,d,o} - \overline{p}_{i,j}\right)^2 \cdot q_{i,j,d,o}}{\sum_{d,o} q_{i,j,d,o}}, \tag{6}$$

where $\overline{p}_{i,j} = \left(\sum_{d,o} p_{i,j,d,o} \cdot q_{i,j,d,o}\right) / \left(\sum_{d,o} q_{i,j,d,o}\right)$ is the quantity-weighted average auction price for CUSIP j in auction i.

The panel "Offer Dispersion (Purchased Bonds)" of Table 4 reports the results from the panel regression of offer dispersion for each bond purchased by the Fed on the same set of eight explanatory variables, controlling for auction fixed effects. Offer Dispersion has a significant correlation with almost all the explanatory variables. Offer dispersion is higher if a bond has a higher specialness, a lower outstanding balance, a wider bid-ask spread, a larger coupon, a larger on/off count, or a longer original maturity. With the exception of specialness, these variables generally point to illiquidity and uncertainty of bond value, which we find intuitive. The positive correlation between offer dispersion and specialness may be due to the fact that bonds on special tend to trade at a yield away from otherwise similar bonds. Thus, dealers may find it more difficult to guess or "model" the Fed's internal spline prices, leading to a higher dispersion in offers.

6 Costs of the Federal Reserve and Dealer Profitability

In this section, we study the cost to the Fed of purchasing the large amount of Treasury securities ($780 billion) in implementing its QE polices from November 12, 2010, to September 9, 2011. We relate these costs to bond characteristics and disaggregate the profits of primary dealers who participate in these auctions. Our measure of costs and profits is relative to the secondary market prices on the days the auctions are closed. Using same-day market prices mitigates the effects of markets events that are hard to control in the time series.

6.1 The costs of the Federal Reserve

To compute the Fed's cost in an individual auction, we first calculate the purchase cost on individual CUSIPs and then take the average costs for all CUSIPs purchased in that auction, weighted by the par amount purchased. We measure the cost to the Fed of purchasing a bond as the difference between the weighted average of accepted prices in QE auctions and the corresponding secondary market price of that bond at the time the auction is closed.[15]

[15] We also measure the cost of purchasing a bond as the difference between the least favorable price accepted by the Fed (also known as the stop-out price) and the corresponding secondary market price. This cost measure quantifies the maximum price the Fed is willing to tolerate to achieve its minimum purchase amount. The cost measure based on stop-out price is around 2 cents per $100 par value higher than that based on the weighed average price, and the correlation between the two measures is as high as 99%. Because of their high correlation, we only report results based on the average purchase price.

As the secondary market quotes are valid only up to a standardized quantity, it is quite possible that the Fed will create price impacts and pay an average purchase price above the ask quote in secondary markets. In addition to the ask quote, we also calculate the costs to the Fed based on the mid quote and the bid quote in the secondary market. The bid is the price at which the Fed can in principle implement its purchases by posting limit orders, at the risk of not being able to execute the target purchases in time. The mid price is a measure of the fair value of the bonds.

Figure 4 and Table 5 present the cost, in cents per \$100 par value, to the Fed for the 139 auctions in our sample. The average cost over all purchase auctions, weighted by auction size, is 0.71, 2.09, and 3.46 cents relative to the ask, mid, and bid quotes in the secondary Treasury market, respectively. To put these average costs into perspective, we observe that the weighted average bid-ask spread for the purchased bonds (weighted by the par amount purchased) is 2.56 cents per \$100 par value during our sample period. Therefore, the average cost to ask of 0.71 cents is only about 28% of the average bid-ask spread. These results reveal that the Fed suffers little market-impact costs in purchasing the huge amount (\$780 billion) of Treasury securities in its QE auctions.[16]

[Figure 4 about here.]

[Table 5 about here.]

Equally interesting is the large dispersion of costs across auctions. The quantity-weighted standard deviations of the Fed's costs to ask, mid, and bid quotes are 11.05, 11.01, and 11.00 cents per \$100 par value, respectively. The average cost to ask for the individual auctions ranges between -43.12 and 46.46. The cost to mid and cost to bid have similarly large ranges. Moreover, the average cost is positive for 46.76%, 55.40%, and 66.91% of the auctions measured using the ask, mid, and bid quotes, respectively. This result suggests that sometimes the Fed receives a more favorable price in QE auctions than in the secondary market.

[16]It may be tempting to argue that this measured cost underestimates the true costs to the Fed, if Treasury prices increase between the announcement date and implementation date of each auction. However, to the extent that the QE policy *aims* to reduce Treasury yields, a price increase in the secondary market is precisely what the Fed wants and in our view should not be part of the cost calculation. What clearly should be counted as a cost is how much the Fed pays above the prevailing secondary market price at the time of the auctions. We use the same logic in our calculation of dealers' profits. This is different from Lou, Yan, and Zhang (2013) who compare issuance auction prices of the Treasury and secondary market prices five days pre-auction.

It is informative to compare the costs of the Fed in QE auctions to the costs of Treasury auctions. Han, Longstaff, and Merrill (2007) report that the Treasury's buyback auctions from March 2000 to April 2002 incur the average cost of 4.38 cents per $100 par value, which is about 70% of the average bid-ask spread of the auctioned bonds. Moreover, the average par amount per auction of the Treasury's buyback operations is $1.5 billion, whereas the average par amount per auction of the Fed's QE purchases in our sample period is more than three times as large, at $5.6 billion. The average cost in QE auctions also compares well with those in issuance auctions of Treasury securities estimated by prior studies. For example, among others, Goldreich (2007) estimates that the average issuance cost of Treasury notes and bonds from 1991 to 2000 is about 3.5 cents per $100 par value, while Cammack (1991) and Nyborg and Sundaresan (1996) provide similar estimates for T-bill issuance auctions.

How does the cost to the Fed vary across different bonds? To answer this question, we estimate panel regressions of the average auction cost of each purchased bond on two sets of explanatory variables. The first set contains the eight bond characteristics. The second set contains three variables of auction outcomes, for each purchased CUSIP and each auction: offer per dealer (the number of winning offers divided by the number of winning dealers), offer dispersion (defined in (6)), and purchase amount (par amount purchased, in $billions). As before, the panel regressions are univariate.

Table 6 reports the results of panel regressions of the average auction cost of each bond purchased by Fed, controlling for auction fixed effects. Among the bond characteristics, only specialness has a significant effect on cost to ask. This result suggest that the Fed's selection criterion based on internal spline-based prices offsets any detectable effect of bond characteristics, except specialness. If specialness is 1% higher on a particular bond, the cost to the Fed to buy this bond increases by about 7 cents per $100 par value, which seems quite large economically. Moreover, the cost to ask on a bond is higher if dealers submit more offers on that bond and if dealers' offers are more dispersed. To the extent that offer dispersion measures the heterogeneity of dealers' values or information, we would expect a higher adverse selection or "bid shading" in the dealers' supply curve, thus a higher cost.

Cost to mid and cost to bid are correlated with most of the bond characteristics. Because cost to ask is equal to cost to bid less the bid-ask spread on each CUSIP, these results may merely reflect the high correlation between bond characteristics and the bid-ask spread. Offer per dealer does not significantly correlate with cost to mid or cost to bid, but offer dispersion does.

[Table 6 about here.]

Lastly, in unreported results, we run OLS regressions of the average cost of each auction on weighted average versions of the explanatory variables used in Table 6. Almost none of the variables are significant, suggesting that even if dealers have any propensity to charge a higher spread on any type of bonds, the Fed substitutes into cheaper offers on other bonds according to the ranking by its internal spline-based prices, leading to comparable costs across bonds.[17]

6.2 Dealer profitability

In this section, we study the profitability of primary dealers in QE auctions. In interpreting the results throughout this section, we use the intuition from Section 3 that the heterogeneity in dealers' profits reflects heterogeneous valuations or information.

For each dealer, we compute the profit margin as

$$\text{Profit Margin} = \frac{\sum_{i,jo} (p_{i,j,d,o} - P_{i,j}) \cdot q_{i,j,d,o}}{\sum_{i,j,o} q_{i,j,d,o}}, \tag{7}$$

where $p_{i,j,d,o}$ and $q_{i,j,d,o}$ are the oth winning offer price and par amount of dealer d for CUSIP j in auction i, respectively, and $P_{i,j}$ is the secondary market price of the CUSIP j at the time auction i is closed. That is, the profit margin is the average, weighted by the amount of each accepted offer, of the differences between the offer price and the corresponding secondary market price of the bond for that offer at the time the auction is closed. We use both the ask and bid prices as the secondary market prices. The profit margin to bid measures the profitability of dealers in selling bonds to the Fed through the QE auctions, rather than selling bonds to investors on the secondary market at the bid price without delay. The profit margin to ask measures the profitability of dealers who buy bonds on the secondary market at the ask price without delay and then sell them to the Fed in the QE auctions. We also use the mid-price to compute dealers' profit margin.

With the profit margins, we calculate the aggregate profit of each dealer as

$$\text{Aggregate Profit} = \text{Profit Margin} \times \text{Offer Amount Accepted}, \tag{8}$$

where the profit margin can be relative to secondary market bid, mid, and ask prices.

[17]To control for the possibility that dealers learn about the bond values or the Fed's internal spline-based prices over time, we also include the auction number in the OLS regression as an explanatory variable (Milgrom and Weber (1982), Ashenfelter (1989), and Han, Longstaff, and Merrill (2007)). We do not find any time trend in the data.

[Table 7 about here.]

Table 7 summarizes the dealer-by-dealer profitability across the 139 QE auctions in our sample period. The first column lists the profitability rankings according to dealers' aggregate profits to bid prices, while the dealer identities are provided in the second column. The third column presents the aggregate par amount each dealer sold to the Fed in billions of dollars. The rest of the columns provides the profit margin in cents per $100 par amount and the aggregate profit in millions of dollars of each dealer, relative to the secondary market bid, mid, and ask prices, respectively.

Complementary to Table 7, Table 8 reports bidding characteristics of each dealer, sorted by their aggregate profits to bid prices. For each dealer, we consider four bidding characteristics: number of auctions participated, number of CUSIPs sold, number of winning offers per auction, and number of winning offers per CUSIPs accepted.

[Table 8 about here.]

Table 7 reveals that the aggregate profits to bid are positive for all dealers. Among the 20 dealers, only one has a negative average profit to mid, and eight have an average negative profit to ask. The concentration of aggregate profits and aggregate amounts of accepted offers among dealers is striking. The top five dealers, Goldman Sachs, Morgan Stanley, Barclays Capital, BNP Paribas, and J.P. Morgan, account for 65% of the $268.8 million total profit to bid of all dealers participating in the 139 QE auctions. The ratio is even higher, about 70% and 96%, if aggregate profits are measured using mid and ask prices, respectively. These five dealers also accounted for 54% of the $776.6 billion total purchases. By contrast, the bottom five dealers (Nomura, Jefferies, Daiwa, Cantor Fitzgerald, and Mizuho, excluding SG Americas and MF Global who participated in QE auctions only after February 2, 2011) account for only 6% of the $268.8 million total profit to bid and 6.6% of the $776.6 billion total par amount purchased. Furthermore, we see in Table 8 that the top five dealers sold bonds to the Fed in over 128 of the 139 QE auctions, and had winning offers on over 129 of 186 CUSIPs purchased by the Fed, with the highest number of winning offers both per auction and per CUSIP. These results strongly suggest the existence of information asymmetry across dealers.

The profit margins reveal further patterns regarding the heterogeneity of dealers. Certain dealers have high profit margins but low aggregate profits due to their lower number of winning offers. For example, RBC, Merrill Lynch, and Daiwa have profit margins to bid over 4.4 cents per $100 par amount, which are above the average profitability of 3.15 cents, but their aggregate profits to bid are all significantly lower than the top five dealers. This pattern suggests that the quantity of offers accepted and the profitability on these offers could be two separate dimensions. For example, as suggested by the stylized model of Section 3, dealers' profit margins margins may well be related to asymmetric information regarding the Fed's internal spline-based prices, whereas the total sale volume may reflect a dealer's activity in Treasuries markets.

To better understand the heterogeneity of dealer profitability, we regress dealers' profit margins on two sets of explanatory variables, at the auction/dealer level (i.e. aggregating CUSIP information). The first set contains the weighted average (by the CUSIP-specific par amount accepted) of bond characteristics: specialness, outstanding balance, bid-ask spread, coupon rate, on/off count, time to maturity, original maturity, and volatility. The second contains two bidding variables: offer per CUSIP and weighted average bid dispersion. We control for auction fixed effects, and report robust t-statistics that correct for serial correlation in the residuals clustered at the auction level in the parentheses.

[Table 9 about here.]

Table 9 reports the results. Most of the weighted average bond characteristic variables are highly significant in explaining variations of dealers' profit margins to bid and mid. The signs of these significant variables imply that certain dealers have higher profitability because they manage to sell bonds that are less liquid (e.g. those with higher bid-ask spreads or larger on/off count) or more difficult to locate (e.g. those with lower outstanding balances). Once the spread component is eliminated, margin to ask is not explained by any of those variables. It seems reasonable to say that dealers' profitability in QE auctions is partly correlated with their market-making profits, measured by the bid-ask spread.

Do different dealers show different bidding behaviors? The heterogeneity of dealers' profits suggests that they should. To answer this question, we estimate panel regressions of two bidding variables, offer per CUSIP and weighted average offer dispersion, on a set of explanatory variables across dealer/auction. The offer per CUSIP is the ratio between the total number of winning offers and the total number of CUSIPs purchased by a dealer d in auction i. For each dealer d in auction i, the weighted average offer dispersion is obtained by computing first the offer dispersion measure for each CUSIP using dealer d's accepted offers on this CUSIP similar to (6), and then the weighted average of such CUSIP-specific dispersion measures using the CUSIP-specific quantity. The explanatory variables are the weighted average of (by the CUSIP-specific par amount accepted) specialness, outstanding balance (in 10 billions of dollars), bid-ask spread, coupon rate, on/off count, time to maturity, original maturity, and volatility.

[Table 10 about here.]

Table 10 reports the results from the panel regression of offer per CUSIP and weighted average offer dispersion. Most of the weighted-average bond characteristics are highly significant in explaining variations of offer per CUSIP. Generally, dealers submit fewer offers on bonds that are less liquid, suggesting that either (a) they face a higher uncertainty of bond value or the Fed's internal spline-based price, or (b) their offers on these bonds are more unattractive, so the Fed substitutes them with more liquid ones. Dealers' weighted average offer dispersion is only mildly correlated with the weighted averages of coupon, on/off count, and original maturity, suggesting that lower liquidity coincides with only marginally higher heterogeneity in dealers' valuations or information.

7 Post-Auction Bond Returns and Liquidity

In this section, we explore the granular cross-section information in our data and study the connection between auction outcomes and post-auction bond prices and liquidity.

Specifically, we run panel regressions of bond returns from before to after auction dates on auction variables, across CUSIP/auction, and controlling for both auction and CUSIP fixed effects. For each auction date t, we calculate the bond return from one day before to one day after the auction, $\log(P_{t+1}) - \log(P_{t-1})$, and the bond return from one day before to five days after the auction, $\log(P_{t+5}) - \log(P_{t-1})$, in percentage points.[18] All days are business days. For each CUSIP and auction, the right-hand variables include total purchased amount (in billions of dollars), offer dispersion, offer per dealer, number of offers, number of dealers, and profit margin to mid.[19] Note that purchase amounts and profit margin to mid reflect the information of both the Fed and the dealers, whereas all other auction variables only reflect the information of the dealers. This panel-regression approach is broadly similar to that of D'Amico and King (2013), but the auction variables are unique to our study.

[18] We stop at the five-day horizon because QE auctions for the same maturity bucket are conducted about every five business days. Longer-horizon returns of a particular bond will likely cover two or more auctions involving that bond, making the results difficult to interpret.

[19] We also run regressions using margin to bid and margin to ask (and also margins based on stop-out prices), and find similar results. It is also the case for the regressions of bond liquidity changes reported in Table 12. In addition, we also run regressions of both bond price and liquidity changes using purchase amount divided by outstanding balance (for each CUSIP) and find similar results.

Table 11 reports the results. Interestingly, auction variables can significantly forecast bond returns. Offer per dealer, number of offers, and number of dealers positively forecast bond returns from one day before to one day after the auction date, suggesting that a higher competitiveness of dealers conveys positive information regarding bond returns in the short term. Purchase amount is either statistically insignificant or significant but small.[20]

By contrast, the return from $t-1$ to $t+5$ is only significantly forecasted by purchase amount. If the Fed's purchase amount of a particular CUSIP is $1 billion more than the purchase of another, the first CUSIP tends to have a cumulative return that is 28–38 basis points higher than that of the second, depending on the particular estimation model. No other auction variable can forecast bond returns beyond the purchase amount, suggesting that information contained in dealers' offers delays quickly.

We caution that the 28–38 bps bond return five days after the auction date should not be taken literally, for two reasons. First, since we do not observe the Fed's demand function (or its internal spline method), we cannot rule out the possibility that certain bonds are bought more because they are perceived as "undervalued" by the Fed. The post-auction returns for those "undervalued" bonds would naturally be higher. Second, each auction is immediately followed by a few other auctions for different maturity buckets, so the five-day return pattern can be partly affected by the outcomes of these immediately subsequent auctions.

[Table 11 about here.]

Do Fed purchases affect liquidity in Treasury markets? To answer this question, we run a similar regression of the cumulative changes in bond liquidity, proxied by the bid-ask spread in basis points, on the same right-hand variables, again controlling for CUSIP and auction fixed effects. A wider bid-ask spread implies worse liquidity. Table 12 reports the results on the change in liquidity, from one day before to one day after the auction (Panel A) and from one day before to five days after the auction (Panel B). We observe that none of the auction variables significantly forecast bond liquidity change, whether it is from $t-1$ to $t+1$ or from $t-1$ to $t+5$. In contrast, purchase amount is positively significant for bond liquidity changes from one day before to five days after auctions. That is, if the Fed buys a larger amount of a particular bond in QE auctions, that bond tends to become less liquid. However, the negative effect on liquidity is small. If the Fed purchases $1 billion more of a particular bond, the bond's spread tends to widen by 0.04–0.05 basis points five days later,

[20]In unreported results, we also find that the same auction variables alone can predict bond returns up to three days after the auction, but this predictability is not statistically significant once the purchase amounts are included on the right-hand side.

a very small amount relative to the average bid-ask spread (2.4 basis points) of Treasury market in our sample period.

[Table 12 about here.]

8 Conclusion

The large scale purchase of Treasury securities by the Federal Reserve, commonly known as quantitative easing (QE), is one of the most dramatic events in the U.S. Treasury market. The Fed uses QE auctions—multi-object, multi-unit, and discriminatory-price auctions—to implement its QE policy. This paper provides an empirical analysis of the outcomes and dealers' strategic behaviors of QE auctions. During our sample period of November 2010 to September 2011, the Fed purchased around $780 billion of Treasury securities, a large fraction of the outstanding amount. Our findings can be summarized as follows:

1. The Fed tends to exclude from QE auctions the most liquid Treasury securities and securities with heightened specialness in repo markets.

2. Among Treasury securities included in QE auctions, transaction volumes tilt toward more liquid ones. In the cross-section, and controlling for the auction fixed effect, a one basis point increase in the relative bid-ask spread of a Treasury bond is associated with a $130 million reduction in the purchase of that bond. A $10 billion higher outstanding balance of a Treasury bond is associated with a $110 million higher purchase.

3. Primary dealers submit heterogeneous offer prices, and the dispersion of these offers is higher on bonds with a wider bid-ask spread and a lower outstanding amount (*less liquid*) and on bonds with a higher specialness (*more liquid*).

4. The average costs to the Fed appear low. Relative to secondary market ask quotes at the close of the auction, the Fed pays an additional 0.7 cents per $100 par value on average. The total dollar value of this cost is about $55 million. Across auctions, the standard deviation of the Fed's costs, measured against to second-market prices, is about 11 cents per $100 par value.

5. Primary dealers on average make profits by selling Treasury securities to the Fed. The top five dealers account for about 96% of all dollar profits made by primary dealers, if measured against the ask quotes in the secondary markets. This figure is 65% and 70% if measured against the bid and mid quotes in the secondary markets, respectively.

6. The profits of primary dealers relative to bid or mid quotes increase in bond illiquidity. This suggests that dealers that make more profits tend to sell more illiquid bonds to the Fed.

7. Treasury returns one day after the auction can be forecasted by the dealers' bidding behavior in the auctions, whereas five-day returns are only predictable by the purchase amount.

8. QE auctions do not seem to have an economically significant effect on bond liquidity.

This paper does not answer all questions on QE auctions, but we believe it is a start. We can see two potential directions to investigate further. One is to construct a more thorough model and derive specific theoretical predictions that can be tested. Structural parameters can then be estimated and used for answering market-design questions. For example, what is the best design of QE auctions to maximize competition among dealers and minimize the Fed's costs? Should the Fed decide to reverse its QE policy, what is the best design to sell its Treasury inventories?

The second potential direction is to dig deeper into the effect of QE auctions on Treasury markets by further exploring the cross-section information in the data. So far, post-auction bond prices are necessarily the joint results of the dealers' supply curves and the Fed's internal spline-based prices. For example, a higher purchase on certain CUSIPs may reflect the Fed's perception or information that these bonds are undervalued. Disentangling the dealers' supply and the Fed's demand is likely to require additional data, such as dealers' offers that are rejected by the Fed. We leave these questions for future research.

Appendix

A Proof of Proposition 1

Under the technical condition of concavity, the first-order condition would give us the optimal strategy.

To derive the optimal strategy β, we take the first-order condition of Π_i^I and get

$$
\begin{aligned}
0 = \frac{d\Pi_i^I}{da_i} &= [1-F(\beta^{-1}(a_i))]^{M-1}[1-F(\gamma^{-1}(a_i))]^{N-M} \\
&+ (a_i - v_i)\left[-(M-1)[1-F(\beta^{-1}(a_i))]^{M-2} f(\beta^{-1}(a_i))\frac{d\beta^{-1}(a_i)}{da_i}[1-F(\gamma^{-1}(a_i))]^{N-M}\right] \\
&+ (a_i - v_i)\left[-[1-F(\beta^{-1}(a_i))]^{M-1}(N-M)[1-F(\gamma^{-1}(a_i))]^{N-M-1} f(\gamma^{-1}(a_i))\frac{d\gamma^{-1}(a_i)}{da_i}\right].
\end{aligned}
\tag{9}
$$

Substituting in $a_i = \beta(v_i)$ and using the fact that $d\beta^{-1}(a_i)/da_i = 1/\beta'(v_i)$, we have the differential equation:

$$
\begin{aligned}
&[1-F(v)]^{M-1}[1-F(\gamma^{-1}(\beta(v)))]^{N-M}\beta'(v) \\
&= (\beta(v) - v)\left[(M-1)[1-F(v)]^{M-2} f(v)[1-F(\gamma^{-1}(\beta(v)))]^{N-M}\right] \\
&\quad + (\beta(v) - v)\left[[1-F(v)]^{M-1}(N-M)[1-F(\gamma^{-1}(\beta(v)))]^{N-M-1} f(\gamma^{-1}(\beta(v)))\gamma^{-1\prime}(\beta(v))\beta'(v)\right].
\end{aligned}
\tag{10}
$$

The above equation can be written as

$$
d\left\{\beta(v)[1-F(v)]^{M-1}[1-F(\gamma^{-1}(\beta(v)))]^{N-M}\right\} = v\, d\left\{[1-F(v)]^{M-1}[1-F(\gamma^{-1}(\beta(v)))]^{N-M}\right\}.
\tag{11}
$$

Integrating the above equation from v to v_0 and rearranging, we obtain (3).

To derive the optimal strategy γ, we take the first-order condition of Π_i^U and get

$$
\begin{aligned}
0 = \frac{d\Pi_i^U}{da_i} &= [1-F(\gamma^{-1}(a_i))]^{N-M-1}\int_{a_i}^{\bar{v}}[1-F(\beta_{v_0}^{-1}(a_i))]^M g(v_0)dv_0 \\
&- (a_i - v_i)[1-F(\gamma^{-1}(a_i))]^{N-M-1}\int_{a_i}^{\bar{v}} M[1-F(\beta_{v_0}^{-1}(a_i))]^{M-1} f(\beta_{v_0}^{-1}(a_i))\frac{d\beta_{v_0}^{-1}(a_i)}{da_i} g(v_0)dv_0 \\
&- (a_i - v_i)(N-M-1)[1-F(\gamma^{-1}(a_i))]^{N-M-2} f(\gamma^{-1}(a_i))\frac{d\gamma^{-1}(a_i)}{da_i}\int_{a_i}^{\bar{v}}[1-F(\beta_{v_0}^{-1}(a_i))]^M g(v_0)dv_0. \\
&- (a_i - v_i)[1-F(\gamma^{-1}(a_i))]^{N-M-1}[1-F(\beta_{a_i}^{-1}(a_i))]^M g(a_i).
\end{aligned}
\tag{12}
$$

Substituting in $a_i = \gamma(v_i)$ and using the fact that $d\gamma^{-1}(a_i)/da_i = 1/\gamma'(v_i)$, we have the differential equation:

$$[1-F(v)]^{N-M-1}\gamma'(v)\int_{\gamma(v)}^{\bar{v}}[1-F(\beta_{v_0}^{-1}(\gamma(v)))]^M g(v_0)dv_0 \tag{13}$$

$$\begin{aligned}
=&-(\gamma(v)-v)[1-F(v)]^{N-M-1}\gamma'(v)\int_{\gamma(v)}^{\bar{v}} M[1-F(\beta_{v_0}^{-1}(\gamma(v)))]^{M-1}f(\beta_{v_0}^{-1}(\gamma(v)))\beta_{v_0}^{-1\prime}(\gamma(v))g(v_0)dv_0\\
&-(\gamma(v)-v)(N-M-1)[1-F(v)]^{N-M-2}f(v)\int_{a_i}^{\bar{v}}[1-F(\beta_{v_0}^{-1}(a_i))]^M g(v_0)dv_0.\\
&-(\gamma(v)-v)[1-F(v)]^{N-M-1}\gamma'(v)[1-F(\beta_{\gamma(v)}^{-1}(\gamma(v)))]^M g(\gamma(v)).
\end{aligned}$$

As in the case of informed dealers, the differential equation can be rewritten as

$$d[\gamma(v)X(v)] = v\,dX(v). \tag{14}$$

In particular, $X(\bar{v}) = 0$. Integrating from v to $\bar{v}$ and rearranging, we obtain (4).

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List of Figures

Figure 1: Example of Timeline of QE Auctions

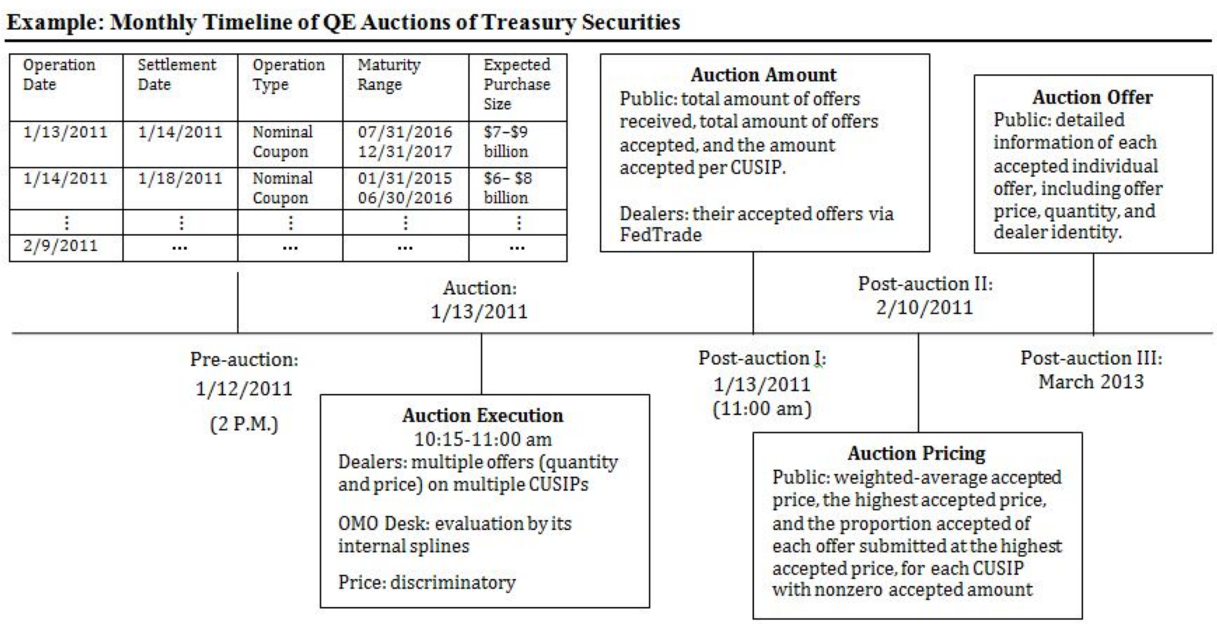
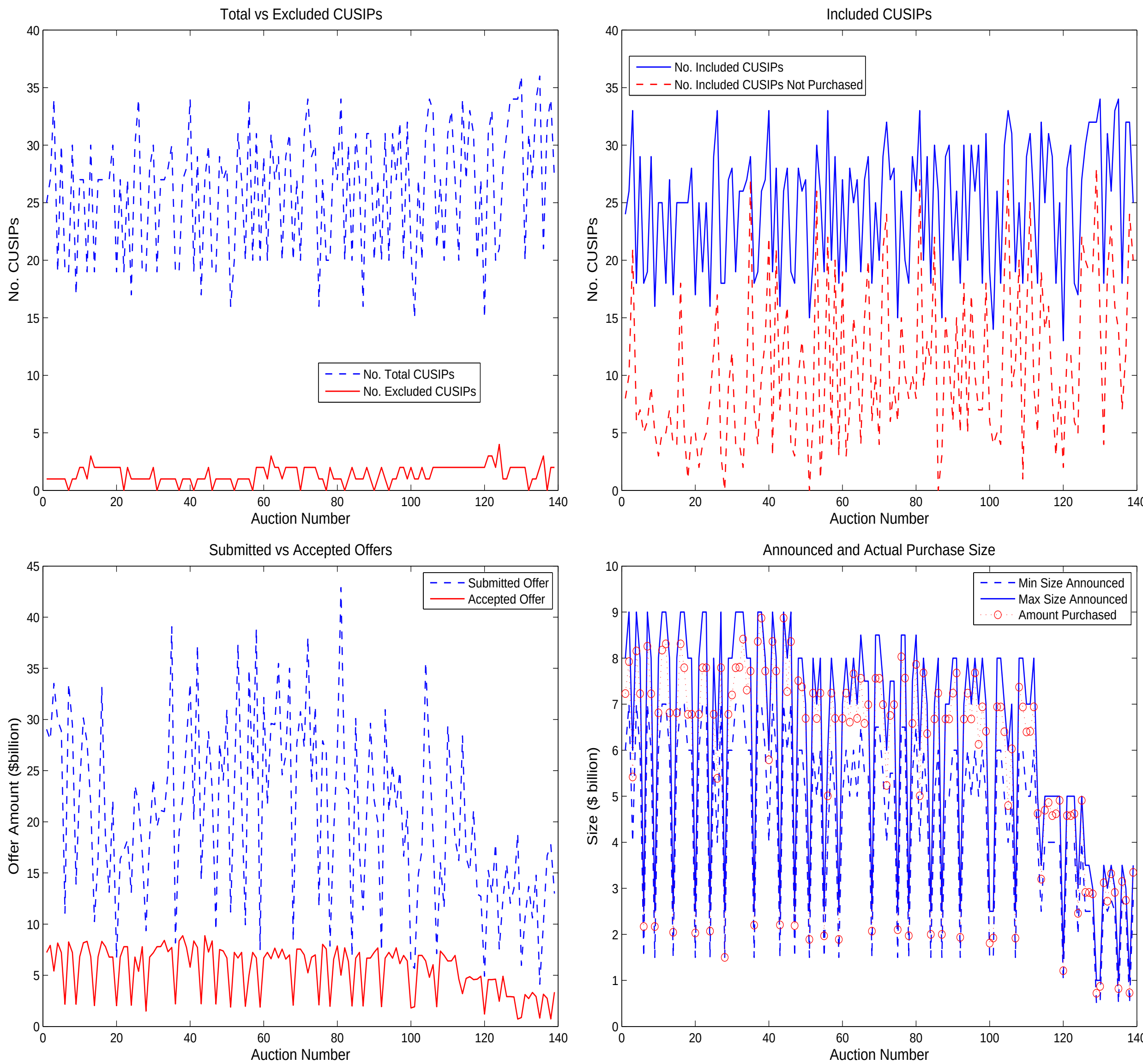
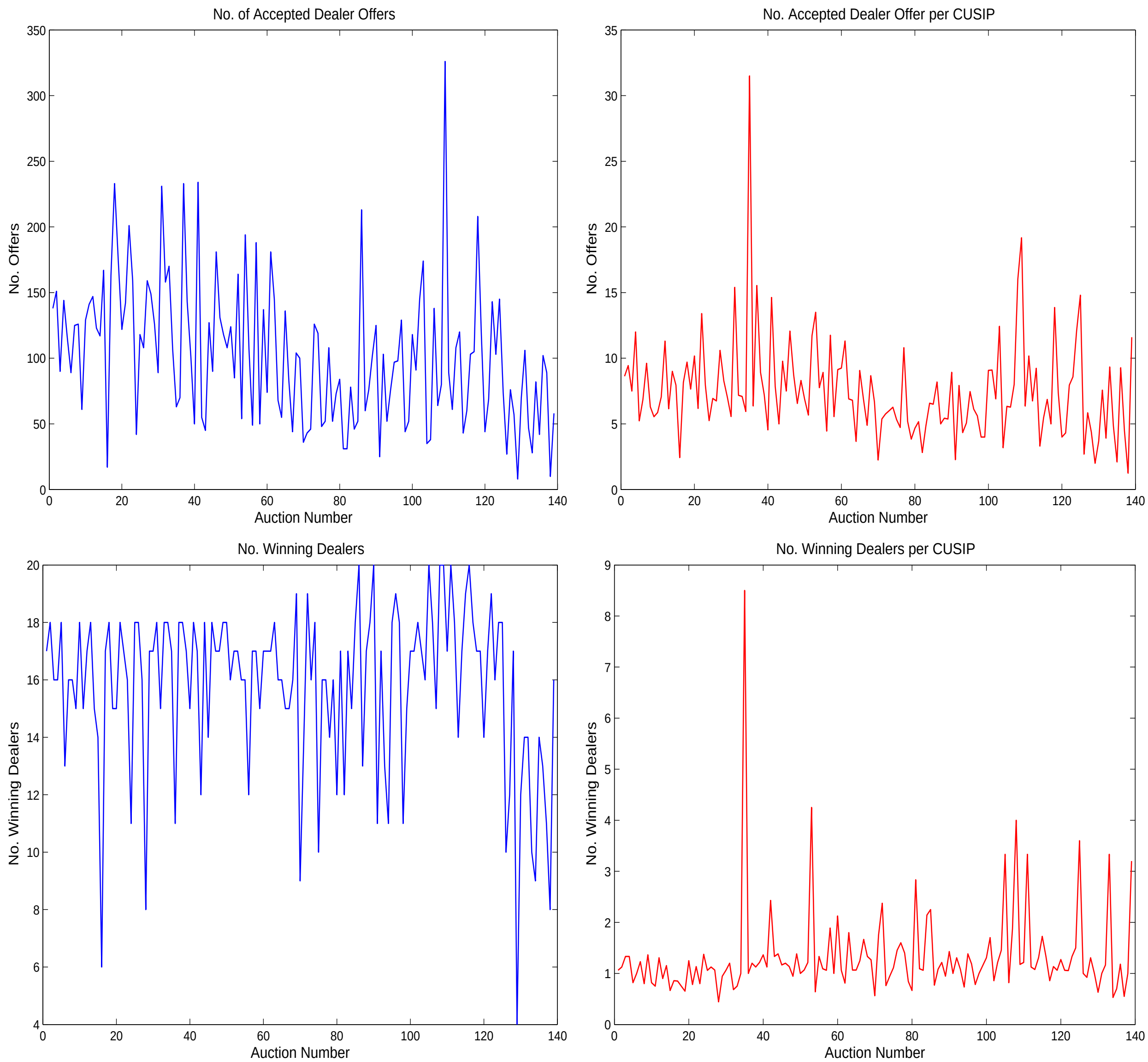


Figure 2: QE Auction: Number of Bonds and Auction Size



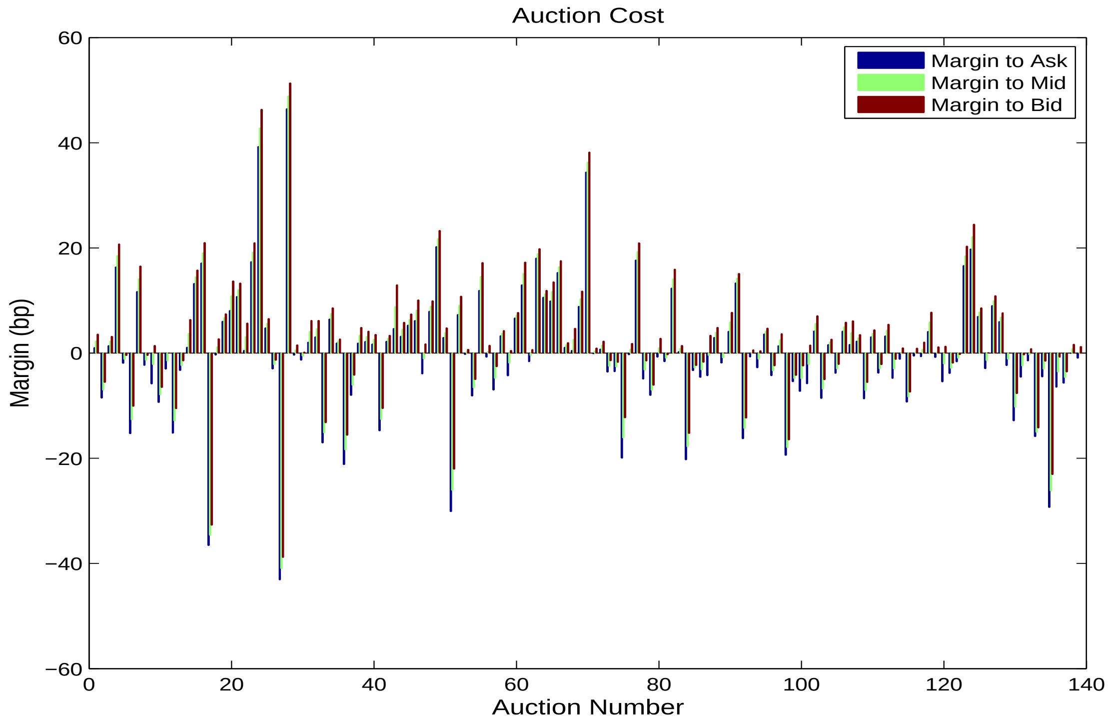
Note: This figure presents descriptive statistics on the number of bonds and auction size for the 139 QE auctions of nominal Treasury securities, from November 12, 2010, to September 9, 2011.

Figure 3: QE Auction: Number of Offers and Dealers



Note: This figure presents descriptive statistics on the number of accepted offers and winning dealers for the 139 QE auctions of nominal Treasury securities, from November 12, 2010, to September 9, 2011.

Figure 4: Auction Cost



Note: This figure presents the cost (in cents per $100 par value) to the Fed in the 139 QE auctions from November 12, 2010, to September 9, 2011. The cost of an individual auction is obtained by first computing the purchase cost for individual CUSIPs and then taking the average (weighted by the par amount purchased) of the costs for all CUSIPs purchased in that auction. The Fed's cost of purchasing a bond is the difference between the weighted average of accepted prices and the corresponding secondary market price of that bond at the time the auction is closed. We use the secondary market ask, mid, and bid prices, quoted closest to the time the auction is closed.

List of Tables

Table 1: Maturity Distribution of Planned Purchases in QE Auctions

Maturity Sectors for QE Auctions of Treasury Securities								
	Nominal Coupon Securities							TIPS
Maturity Sector (Years)	1.5–2.5	2.5–4	4–5.5	5.5–7	7–10	10–17	17–30	1.5–30
Percentage	5%	20%	20%	23%	23%	2%	4%	3%

Note: This table provides the maturity distribution of planned purchases in QE Auctions of Treasury debt over our sample period (November 12, 2010–September 9, 2011), announced on November 3, 2010 by the Fed. The on-the-run 7-year note will be considered part of the 5.5- to 7-year sector, and the on-the-run 10-year note will be considered part of the 7- to 10-year sector.

Table 2: Correlations of CUSIP-Level Variables

	Specialness	Outstanding Balance	Bid-Ask	Coupon	On/Off Count	Time to Maturity	Original Maturity
A: Pooled Correlation							
Specialness	1.00						
Outstanding Balance	-0.12	1.00					
Bid-Ask Spread	0.07	-0.78	1.00				
Coupon	0.22	-0.84	0.84	1.00			
On/Off Count	0.17	-0.57	0.69	0.79	1.00		
Time to Maturity	-0.13	-0.52	0.43	0.35	-0.10	1.00	
Original Maturity	0.11	-0.84	0.82	0.87	0.55	0.71	1.00
Volatility	-0.14	-0.48	0.40	0.34	-0.08	0.80	0.60
B: Average of Auction-Level Correlation							
Specialness	1.00						
Outstanding Balance	-0.23	1.00					
Bid-Ask Spread	0.05	-0.61	1.00				
Coupon	0.15	-0.65	0.73	1.00			
On/Off Count	0.05	-0.66	0.82	0.87	1.00		
Time to Maturity	-0.11	0.05	0.07	0.09	-0.04	1.00	
Original Maturity	0.10	-0.62	0.72	0.86	0.82	0.20	1.00
Volatility	-0.22	0.36	-0.21	-0.24	-0.34	0.83	-0.12

Note: This table reports the correlations of bond characteristic variables. Panel A reports the correlations by pooling the observations across CUSIP/Auction, while Panel B reports correlations by first computing the correlation matrix across CUSIPs for each auction and then taking averages across auctions in order to control for the effect of panel data. Specialness is the difference between the general repo rate and special repo rate on the CUSIP, in percentage points. Outstanding balance is the total outstanding par amount of the bond (in 10 billions of dollars). Bid-ask spread is the difference between the secondary market ask and bid quotes of a bond normalized by the mid-quote, denoted in basis points. Coupon is in percentage points. On/off count of a bond is the cumulative number of new issuance of bonds with the same coupon rate and original maturity. Time to maturity and original maturity are both measured in years. Volatility is the standard deviation of bond returns, using the series of mid-prices of secondary market quotes each day, during the five trading days prior to the auction date. The secondary market prices have the closest quoting time to the close of auction. The sample period is from November 12, 2010, to September 9, 2011.

Table 3: Panel Logit Regression for the Inclusion of Bonds in QE Auctions

Explanatory Variable	Estimate	N	Pseudo R^2
Specialness	-7.376**	3,127	0.0540
	(-2.683)		
Outstanding Balance	0.031	3,127	0.0276
	(0.321)		
Bid-Ask Spread	0.233**	3,127	0.0373
	(2.922)		
Coupon	0.072	3,127	0.0295
	(1.374)		
On/Off Count	0.001	3,127	0.0275
	(0.226)		
Time to Maturity	-0.078**	3,127	0.0299
	(-3.445)		
Original Maturity	0.013	3,127	0.0282
	(0.905)		

Note: This table reports the results from the panel logit regression of whether a bond is included in an auction (yes=1, no=0) on a set of explanatory variables, with z-statistics in the parentheses. The auction fixed effects are included. Specialness is the difference between the general repo rate and special repo rate on the CUSIP, in percentage points. Outstanding balance is the total outstanding par amount of the bond in 10 billions of dollars. Bid-ask spread is the difference between the secondary market ask and bid quotes of a bond normalized by the mid-quote, denoted in basis points. Coupon is in percentage points. On/off count of a bond is the cumulative number of new issuance of bonds with the same coupon rate and original maturity. Time to maturity and original maturity are both measured in years. The secondary market prices have the closest quoting time to the close of auction. The sample period is from November 12, 2010, to September 9, 2011. We exclude bonds for which no quotations of special repo rates are available. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^{+}$ for $p < 0.1$, where p is the p-value.

Table 4: Panel Regression for Purchase Amount and Bidding Behavior across CUSIP/Auction

Explanatory Variable	Purchase Amount (Included Bonds)		Purchase Amount (Purchased Bonds)		Offer Dispersion (Purchased Bonds)	
	Estimate	R^2	Estimate	R^2	Estimate	R^2
Specialness	0.89	0.03	2.53*	0.11	2.78*	0.39
	(1.44)		(2.03)		(2.40)	
Outstanding Balance	0.11**	0.06	0.16**	0.13	-0.10**	0.39
	(16.24)		(9.19)		(-3.52)	
Bid-Ask Spread	-0.13**	0.11	-0.19**	0.21	0.06*	0.39
	(-15.75)		(-13.76)		(2.32)	
Coupon	-0.06**	0.07	-0.10**	0.15	0.06**	0.40
	(-19.31)		(-14.61)		(3.68)	
On/Off Count	-0.01**	0.11	-0.02**	0.21	0.01**	0.39
	(-16.27)		(-15.89)		(3.17)	
Time to Maturity	0.01	0.03	0.01	0.10	0.02	0.39
	(0.15)		(1.50)		(1.13)	
Original Maturity	-0.02**	0.06	-0.03*	0.15	0.02**	0.40
	(-20.35)		(-16.08)		(3.53)	
Volatility	-0.02	0.03	0.32	0.10	-0.86	0.39
	(-0.13)		(0.88)		(-1.39)	
N	3261		1854		1854	

Note: This table reports the panel regressions of the par amount accepted (in billions of dollars) of each bond included in an auction, as well as Offer Dispersion of each bond purchased by Fed, on a number of potential explanatory variables, controlling for auction fixed effects. Robust t-statistics that correct for serial correlation in the residuals clustered at the auction level are reported in parentheses. Specialness is the difference between the general repo rate and special repo rate on the CUSIP, in percentage points. Outstanding balance is the total outstanding par amount of the bond (in 10 billions of dollars). Bid-ask spread is the difference between the secondary market ask and bid quotes of a bond normalized by the mid-quote, denoted in basis points. Coupon is in percentage points. On/off count of a bond is the cumulative number of new issuance of bonds with the same coupon rate and original maturity. Time to maturity and original maturity are both measured in years. Volatility is the standard deviation of bond returns, using the series of mid-prices of secondary market quotes each day, during the five trading days prior to the auction date. The secondary market prices have the closest quoting time to the close of auction. The sample period is from November 12, 2010, to September 9, 2011. The first panel, denoted "Included Bonds", uses the sample of all included bonds with both zero and nonzero purchase amounts, while the second and third panels, denoted "Purchased Bonds", use the sample of bonds with nonzero purchase amounts. We exclude bonds for which no quotations of special repo rates are available. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^{+}$ for $p < 0.1$, where p is the p-value.

Table 5: Auction Cost

	Quantity-Weighted Mean	Quantity-Weighted Standard Deviation	Min	Max
Cost to Ask	0.71	11.05	-43.12	46.46
Cost to Mid	2.09	11.01	-40.99	48.92
Cost to Bid	3.46	11.00	-38.86	51.39

Note: This table presents summary statistics of the cost (in cents per $100 par value) to the Fed in the 139 QE auctions from November 12, 2010, to September 9, 2011. The cost of an individual auction is obtained by first computing the purchase cost for individual CUSIPs and then taking the average (weighted by the par amount purchased) of the costs for all CUSIPs purchased in that auction. The Fed's cost of purchasing a bond is the difference between the weighted average of accepted prices and the corresponding secondary market price of that bond at the time the auction is closed. We use the secondary market ask, mid, and bid prices, quoted closest to the time the auction is closed. The quantity-weighted mean and standard deviation is computed as the mean and standard deviation across the 139 QE auctions, weighted by auction sizes.

Table 6: Panel Regression of Auction Cost across CUSIP/Auction

Explanatory Variables	Cost to Ask		Cost to Mid		Cost to Bid	
(N=1854)	Estimate	R^2	Estimate	R^2	Estimate	R^2
Specialness	7.02*	0.94	14.14**	0.95	21.27**	0.93
	(2.22)		(3.50)		(4.00)	
Outstanding Balance	0.06	0.95	-0.76**	0.95	-1.57**	0.94
	(0.42)		(-4.92)		(-8.86)	
Bid-Ask Spread	-0.13	0.95	0.60**	0.95	1.33**	0.95
	(-1.18)		(5.34)		(11.32)	
Coupon	0.05	0.95	0.52**	0.95	0.98**	0.95
	(0.60)		(6.07)		(11.14)	
On/Off Count	-0.00	0.95	0.07**	0.95	0.14**	0.95
	(-0.27)		(5.58)		(10.83)	
Time to Maturity	0.18	0.95	0.12	0.95	0.06	0.93
	(1.48)		(1.00)		(0.49)	
Original Maturity	0.02	0.95	0.16**	0.95	0.30**	0.95
	(0.87)		(5.99)		(11.00)	
Volatility	1.81	0.95	-3.38	0.95	-8.58*	0.93
	(0.47)		(-0.93)		(-2.24)	
Offer per Dealer	0.47*	0.95	0.34^{+}	0.95	0.22	0.93
	(2.22)		(1.66)		(1.00)	
Offer Dispersion	0.60**	0.95	0.72**	0.95	0.85**	0.93
	(4.56)		(5.32)		(5.52)	

Note: This table reports results from panel regressions of the average auction cost of each bond purchased by Fed on a set of explanatory variables, across CUSIP/auction, controlling for auction fixed effects. Robust t-statistics that correct for serial correlation in the residuals clustered at the auction level are reported in parentheses. The cost of an individual auction is obtained by first computing the purchase cost for individual CUSIPs and then the average (weighted by the par amount purchased) of the costs for all CUSIPs purchased in that auction. The cost to Fed of purchasing a bond is the difference between the weighted-average accepted price and the corresponding secondary market (ask, mid, and bid) price. Specialness is the difference between the general repo rate and special repo rate on the CUSIP, in percentage points. Outstanding balance is the total outstanding par amount of the bond (in 10 billions of dollars). Bid-ask spread is the difference between the secondary market ask and bid quotes of a bond normalized by the mid-quote, denoted in basis points. Coupon is in percentage points. On/off count of a bond is the cumulative number of new issuance of bonds with the same coupon rate and original maturity. Time to maturity and original maturity are both measured in years. Volatility is the standard deviation of bond returns, using the series of mid-prices of secondary market quotes each day, during the five trading days prior to the auction date. The secondary market prices have the closest quoting time to the close of auction. Offer per dealer is the total number of winning offers divided by the total number of winning dealers, for each bond of each auction. Offer Dispersion is defined as in (6). The sample period is from November 12, 2010, to September 9, 2011. Bonds with no quotations of special repo rates are excluded. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^{+}$ for $p < 0.1$, where p is the p-value.

Table 7: Dealer Profitability

Rank by Aggregate Profits to Bid	Dealer	Aggregate Offer ($ billion)	Aggregate Profit to Bid ($ million)	Profit Margin to Bid (Cents per 100 dollars)	Aggregate Profit to Mid ($ million)	Profit Margin to Mid (Cents per 100 dollars)	Aggregate Profit to Ask ($ million)	Profit Margin to Ask (Cents per 100 dollars)
1	Goldman Sachs	143.61	57.74	4.02	38.52	2.68	19.30	1.34
2	Morgan Stanley	125.88	53.3	4.23	37.99	3.02	22.67	1.80
3	Barclays Capital	69.57	25.15	3.62	11.19	1.61	-2.77	-0.40
4	BNP Paribas	48.49	20.24	4.17	13.93	2.87	7.61	1.57
5	J.P. Morgan	32.91	17.82	5.41	12.14	3.69	6.45	1.96
6	Credit Suisse	82.97	17.41	2.10	8.35	1.01	-0.72	-0.09
7	RBS	59.27	15.55	2.62	7.46	1.26	-0.63	-0.11
8	Deutsche Bank	24.24	10.11	4.17	5.34	2.20	0.57	0.24
9	RBC	17.92	7.89	4.40	5.43	3.03	2.97	1.66
10	Merrill Lynch	16.78	7.51	4.47	4.89	2.91	2.26	1.35
11	Citigroup	49.61	7.35	1.48	0.43	0.09	-6.5	-1.31
12	HSBC	22.55	6.54	2.9	4.11	1.82	1.67	0.74
13	UBS	25.61	5.36	2.10	2.28	0.89	-0.80	-0.31
14	Nomura	19.08	4.86	2.55	2.77	1.45	0.68	0.36
15	Jefferies	12.92	4.76	3.69	2.99	2.32	1.22	0.94
16	Daiwa	8.71	3.84	4.41	2.81	3.23	1.77	2.04
17	Cantor Fitzgerald	5.80	1.83	3.16	1.10	1.89	0.36	0.62
18	Mizuho	4.74	0.83	1.76	0.32	0.68	-0.19	-0.41
19	SG Americas	3.77	0.51	1.37	0.15	0.40	-0.21	-0.56
20	MF Global	2.21	0.10	0.44	-0.12	-0.55	-0.34	-1.53
Average		38.83	13.44	3.15	8.10	1.82	2.77	0.50

Note: This table summarizes the dealer profitability across the 139 QE auctions in our sample period. For each dealer, we compute the profit margin as the average (weighted by the amount of each accepted offer) of the differences between the offer price and the corresponding secondary market (bid, mid, and ask) price of the bond for that offer at the time the auction is closed. The aggregate profit of each dealer is computed as the product between the profit margin and offer amount accepted. The profitability rankings of dealers are determined by their aggregate profits to bid prices. The secondary market prices employed have the closest quoting time to the close of auction. The sample period is from November 12, 2010, to September 9, 2011.

Table 8: Bidding Characteristics across Dealers

Dealer Rank by Aggregate Profits to Bid	Dealer	Number of Auctions	Number of CUSIPs	Number of Bids per Auction	Number of Bids per CUSIP
1	Goldman Sachs	138	147	11.70	10.99
2	Morgan Stanley	128	129	5.87	5.82
3	Barclays Capital	131	144	7.18	6.53
4	BNP Paribas	131	174	31.61	23.8
5	J.P. Morgan	131	137	4.87	4.66
6	Credit Suisse	132	140	5.70	5.37
7	RBS	120	120	4.91	4.91
8	Deutsche Bank	113	125	4.60	4.16
9	RBC	103	127	4.24	3.44
10	Merrill Lynch	114	130	4.76	4.18
11	Citigroup	124	135	5.31	4.88
12	HSBC	117	114	3.33	3.42
13	UBS	106	117	4.33	3.92
14	Nomura	116	117	3.31	3.28
15	Jefferies	116	108	3.31	3.56
16	Daiwa	89	81	2.97	3.26
17	Cantor Fitzgerald	101	96	3.35	3.52
18	Mizuho	90	80	3.29	3.70
19	SG Americas	51	45	2.45	2.78
20	MF Global	40	44	1.98	1.80
Average		110	116	5.95	5.40

Note: This table presents bidding characteristics of dealers, ranked by their aggregate profits to secondary market bid prices. Four bidding characteristic variables are included, including the number of auctions, number of CUSIPs, number of winning offers per auction, and number of winning offers per CUSIPs accepted, for each dealer. The secondary market prices employed have the closest quoting time to the close of auction. The sample period is from November 12, 2010, to September 9, 2011.

Table 9: Panel Regression of Dealer Profitability across Dealer/Auction

Explanatory Variable	Margin to Bid		Margin to Mid		Margin to Ask	
(N=1962)	Estimate	R^2	Estimate	R^2	Estimate	R^2
Weighted Average Specialness	-0.009	0.963	0.010	0.968	0.030	0.971
	(-0.295)		(0.418)		(1.325)	
Weighted Average Outstanding Balance	-0.017**	0.966	-0.009**	0.969	-0.001	0.971
	(-5.756)		(-3.685)		(-0.320)	
Weighted Average Bid-Ask Spread	0.132**	0.969	0.063**	0.970	-0.007	0.971
	(7.178)		(3.540)		(-0.388)	
Weighted Average Coupon	0.011**	0.970	0.006**	0.971	0.001	0.971
	(6.948)		(3.925)		(0.754)	
Weighted Average On/Off Count	0.001**	0.969	0.001**	0.970	0.000	0.971
	(7.198)		(3.815)		(0.100)	
Weighted Average Time to Maturity	-0.001	0.963	-0.001	0.968	0.000	0.971
	(-0.887)		(-0.423)		(0.059)	
Weighted Average Original Maturity	0.003**	0.969	0.001**	0.970	0.000	0.971
	(6.082)		(3.252)		(0.340)	
Weighted Average Volatility	-0.113**	0.964	-0.078**	0.969	-0.042	0.971
	(-3.952)		(-2.755)		(-1.350)	
Offer per CUSIP	-0.003**	0.964	-0.002**	0.969	-0.001^{+}	0.971
	(-3.963)		(-3.074)		(-1.924)	
Weighted Average Offer Dispersion	0.001	0.963	0.001	0.969	0.001	0.971
	(0.744)		(0.644)		(0.516)	

Note: This table reports the results for panel regressions of the dealer profit margins on a set of explanatory variables across dealer/auction, controlling for auction fixed effects. Robust t-statistics that correct for serial correlation in the residuals clustered at the auction level are reported in parentheses. The explanatory variables include the weighted averages (by the CUSIP-specific par amount accepted) of CUSIP-level specialness, outstanding balance (in 10 billions of dollars), bid-ask spread, coupon rate, on/off count, time to maturity, original maturity, and volatility, as well as offer per CUSIP and weighted average offer dispersion. The secondary market prices employed have the closest quoting time to the close of auction. The sample period is from November 12, 2010, to September 9, 2011. We exclude bonds for which no quotations of special repo rates are available. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^{+}$ for $p < 0.1$, where p is the p-value.

Table 10: Panel Regression for Dealer Bidding Behavior across Dealer/Auction

Explanatory Variable (N=1962)	Offer per CUSIP		Weighted Average Offer Dispersion	
	Estimate	R^2	Estimate	R^2
Weighted Average Specialness	-0.06	0.16	0.54	0.51
	(-0.09)		(0.49)	
Weighted Average Outstanding Balance	0.17**	0.17	-0.15	0.52
	(3.67)		(-1.59)	
Weighted Average Bid-Ask Spread	-1.28**	0.17	0.31	0.51
	(-4.24)		(0.50)	
Weighted Average Coupon	-0.09**	0.17	0.09*	0.52
	(-3.84)		(2.37)	
Weighted Average On/Off Count	-0.01**	0.18	0.01^{+}	0.52
	(-4.42)		(1.70)	
Weighted Average Time to Maturity	-0.01	0.16	0.04	0.51
	(-0.43)		(1.56)	
Weighted Average Original Maturity	-0.03**	0.18	0.02^{+}	0.52
	(-3.93)		(1.82)	
Weighted Average Volatility	0.28	0.16	0.06	0.51
	(0.64)		(0.08)	

Note: This table reports the results from the panel regressions of offer per CUSIP and weighted average offer dispersion on a set of explanatory variables, across dealer/auction, controlling for auction fixed effects. Robust t-statistics that correct for serial correlation in the residuals clustered at the auction level are reported in parentheses. Offer per CUSIP is the ratio between the total number of winning offers and the total number of CUSIPs purchased by a dealer d in auction i. Also for each dealer d in auction i, the weighted average offer dispersion is obtained by computing first the offer dispersion measure for each CUSIP using dealer d's accepted offers on this CUSIP similar to (6), and then the weighted average of such CUSIP-specific dispersion measures using the CUSIP-specific quantity. The explanatory variables are the weighted averages (by the CUSIP-specific par amount accepted) of CUSIP-level specialness, outstanding balance, bid-ask spread, coupon rate, on/off count, time to maturity, original maturity, and volatility. The secondary market prices employed have the closest quoting time to the close of auction. The sample period is from November 12, 2010, to September 9, 2011. We exclude bonds for which no quotations of special repo rates are available. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^{+}$ for $p < 0.1$, where p is the p-value.

Table 11: Auction Variables and Post-Auction Bond Returns

	A: 1-day Before to 1-day After					
Purchase Amount	-0.0016	-0.0026	-0.0082*	-0.0062$^+$	-0.0008	-0.0007
	(-0.7173)	(-1.1118)	(-2.2484)	(-1.9700)	(-0.3557)	(-0.3120)
Offer Dispersion	0.0038					
	(1.2509)					
Offer per Dealer		0.0083$^+$				
		(1.7889)				
No. of Offers			0.0011*			
			(2.2799)			
No. of Dealers				0.0020*		
				(2.0352)		
Margin-to-Mid					0.0003	
					(0.2108)	
R^2	0.9878	0.9879	0.9879	0.9878	0.9878	0.9878
	B: 1-day Before to 5-day After					
Purchase Amount	0.2883**	0.2842**	0.3466*	0.3801*	0.2804**	0.2849**
	(2.6642)	(2.6550)	(2.3549)	(2.5638)	(2.6441)	(2.6928)
Offer Dispersion	-0.0137					
	(-0.7622)					
Offer per Dealer		0.0031				
		(0.1539)				
No. of Offers			-0.0090			
			(-0.9117)			
No. of Dealers				-0.0346$^+$		
				(-1.7855)		
Margin-to-Mid					0.0168	
					(1.1087)	
R^2	0.7147	0.7146	0.7156	0.7170	0.7158	0.7146

Note: This table reports the panel regressions of bond returns from $t-1$ to $t+1$ (Panel A) and from $t-1$ to $t+5$ (Panel B), controlling for both CUSIP and auction fixed effects. The bond returns are cumulative and in units of percentage points. For each CUSIP and each auction, right-hand variables include purchase amount, offer dispersion, offer per dealer, number of offers, number of dealers, and margin to mid. Purchase amount is in billions of dollars, and the other variables are defined as before. The sample period is from November 12, 2010, to September 9, 2011, with the sample size of 1952. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^+$ for $p < 0.1$, where p is the p-value.

Table 12: Auction Variables and Post-Auction Bond Liquidity

	A: 1-day Before to 1-day After					
Purchase Amount	0.0076	0.0109	0.0267	0.0033	0.0056	0.0050
	(0.4881)	(0.6954)	(1.3431)	(0.1696)	(0.3732)	(0.3320)
Offer Dispersion	-0.0107					
	(-0.7301)					
Offer per Dealer		-0.0260				
		(-1.3217)				
No. of Offers			-0.0032			
			(-1.4206)			
No. of Dealers				0.0006		
				(0.1103)		
Margin-to-Mid					-0.0024	
					(-0.4745)	
R^2	0.2960	0.2971	0.2965	0.2958	0.2959	0.2958
	B: 1-day Before to 5-day After					
Purchase Amount	0.0429$^+$	0.0459*	0.0515$^+$	0.0480$^+$	0.0465*	0.0463*
	(1.9014)	(2.0526)	(1.8092)	(1.7115)	(2.1310)	(2.1270)
Offer Dispersion	0.0141					
	(0.8997)					
Offer per Dealer		0.0015				
		(0.0927)				
No. of Offers			-0.0008			
			(-0.2755)			
No. of Dealers				-0.0006		
				(-0.0956)		
Margin-to-Mid					-0.0007	
					(-0.1432)	
R^2	0.3638	0.3635	0.3635	0.3635	0.3635	0.3635

Note: This table reports the panel regressions of changes of bond liquidity from $t-1$ to $t+1$ (Panel A) and from $t-1$ to $t+5$ (Panel B), controlling for both CUSIP and auction fixed effects. Bond liquidity is proxied by the bid-ask spread, in basis points. For each CUSIP and each auction, right-hand variables include purchase amount, offer dispersion, offer per dealer, number of offers, number of dealers, and margin to mid. Purchase amount is in billions of dollars, and the other variables are defined as before. The sample period is from November 12, 2010, to September 9, 2011, with the sample size of 1952. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^{+}$ for $p < 0.1$, where p is the p-value.