QE Auctions of Treasury Bonds*

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Abstract

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

JEL classification: G12, G13

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The Federal Reserve (Fed) uses auctions to implement its quantitative-easing purchases of Treasury bonds. To evaluate dealers' offers on multiple bonds, the Fed relies on its internal yield-curve model, fitted to secondary market bond prices. Using a proprietary dataset of QE auctions from November 2010 to September 2011, we find that the Fed pays 0.71–2.73 cents per $100 par value above the secondary market ask prices. A one-standard-deviation increase in bond "cheapness"—how much the bond market price is below a yield-curve-model-implied value—increases auction costs by 6.3 cents per $100 par value, controlling for standard covariates. We further document great heterogeneity of profit margins across dealers with comparable sale amounts, and link this heterogeneity to cheapness. Our results are consistent with dealers' strategic bidding behaviors based on their information about the Fed's relative valuations of multiple bonds.

1 Introduction

One of the most significant events in the history of the U.S. Treasury market is the Federal Reserve (Fed)'s large-scale asset purchase programs of long-term Treasury securities since the 2008 financial crisis, commonly known as "quantitative easing" (QE).[1] Up to September 2011, the end of the sample period in our study, the Fed purchased \$1.19 trillion of Treasury bonds,[2] 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. Given their sheer scale, these purchase operations must be conducted in a manner that encourages competitive pricing to avoid excessive execution costs and undesirable burdens on U.S. taxpayers (Potter (2013)).

To purchase such huge amounts of Treasury bonds in a relatively short time window, the Fed used an auction mechanism that involves buying multiple bonds (CUSIPs) in a single auction. In this paper, we quantify the costs of QE auctions and investigate their economic determinants. The unique feature of QE auctions is that the Fed evaluates offers on multiple bonds using its internal yield curve model and secondary market bond prices (Sack (2011)). We provide substantive evidence that the Fed's costs in QE auctions are increasing in bond "cheapness"—how much the bond market price is below a yield-curve-model-implied value. Our results are consistent with dealers' strategic bidding behaviors based on their information about the Fed's relative valuations of multiple bonds.

QE auctions are organized as a series of multi-object, multi-unit, and discriminatory-price auctions, implemented by the Federal Reserve Bank of New York. The only direct participants are primary dealers recognized by the Fed. 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. Multiple offers, up to nine on each bond, can be submitted across all eligible securities simultaneously. Holding a single simultaneous auction for multiple CUSIPs offers much faster execution than holding separate auctions for individual CUSIPs.

To evaluate offers across multiple bonds, the Fed compares the offered prices to its *internal benchmark prices*, according to the Federal Reserve Bank of New York. That is, after adjusting for its internal benchmark prices, the Fed treats different CUSIPs as perfect substitutes. Moreover, the Fed's internal benchmark prices are calculated from a confidential

[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] In this paper, we use "bonds" to refer to Treasury securities with maturity above one year, without distinguishing "Treasury notes" and "Treasury bonds."

spline model, fitted on the secondary market prices of Treasury securities. Taking market bond prices into account helps the Fed to identify "undervalued" securities that are particularly suitable for the Fed to hold. On the other hand, although the Fed's exact yield-fitting model is confidential, the use of publicly available bond prices as model inputs can make the Fed's relative valuations on different bonds partly predictable by the market, especially the primary dealers, for a few reasons. First, fixed-income investors and dealers routinely fit yield-curve models to evaluate the cheapness or richness of different bonds; hence, they have in-depth professional knowledge of these models.[3] Second, primary dealers have years of experience interacting with the Fed through its permanent and temporary open market operations. Third, it is not uncommon for former Fed employees to work for primary dealers, after probationary periods.

Our empirical analysis employs a propriety dataset that 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 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 costs at the aggregate level, but also the granular heterogeneity across auctions, bonds, and dealers.

We measure the costs to the Fed by the difference between the accepted offer prices and the secondary market prices, weighted by the accepted quantity. The secondary market prices are obtained from the Federal Reserve Bank of New York, quoted at 8:40am, 11:30am, 2:15pm, and 3:30pm. The vast majority of QE auctions close at 11am. So for those auctions, our auction costs measured relative to the closest ask price in the secondary market at 11:30am can be viewed as the "realized costs" of the Fed 30 minutes after the auction, or interpreted as the profit of dealers in selling bonds to the Fed at 11am and then covering their short positions in the secondary markets 30 minutes later (see Hasbrouck (2007) for a discussion of realized cost). We also use the secondary market prices at 2:15pm and 3:30pm to compute auction costs. On average, the Fed pays 0.71 cents per $100 par value above secondary market ask prices near the close of the auction, 2.73 cents above the 2:15pm

[3]See Duarte, Longstaff, and Yu (2007) for studies of the yield curve arbitrage strategy of fixed-income hedge funds.

secondary market ask prices, and 2.15 cents above the 3:30pm secondary market ask prices.

The auction price markups also vary substantially across the 139 QE auctions, with a standard deviation of 10-20 cents per $100 par value. A natural question is what drives the time variation in auction costs. Recall that the unique feature of QE auctions is that the Fed values the offers across bonds based on internal benchmark prices, which we conjecture are partly predictable by the market. Although we do not observe the Fed's model, we construct a bond cheapness measure using standard techniques. To the extent that the actual model and data used by the Fed and the dealers are strictly more accurate, our estimated effect of bond cheapness on auction costs would be conservative. Specifically, we first fit a Svensson (1994) yield curve model at the beginning of each auction day. Then, for each CUSIP, we measure its cheapness by the difference between the fitted-yield-curve-implied price and the secondary market ask price, in cents per $100 par value. Our fitted yield curve is highly correlated with the popular "GSW" (Gurkaynak, Sack, and Wright (2007)) yield curve maintained by the Fed.[4]

Besides cheapness, we also take into account two standard economic channels of price markup. One is bond value uncertainty, measured by the volatility of bond returns during the five days before the auction date. Models of common value auctions (e.g., Wilson (1968) and Ausubel, Cramton, Pycia, Rostek, and Weretka (2013)) suggest that a higher value uncertainty increases auction price markup. In addition, we consider a few measures of bond illiquidity and scarcity, including the specialness (how costly it is to borrow a particular bond in the repo market), the bid-ask spread, and the outstanding balance of a particular bond. We expect the auction cost to be higher if the bond is more special or is less liquid.

We run panel regressions of the auction price markup across bonds and auctions on bond cheapness, as well as volatility, specialness, bid-ask spread, and outstanding balance, controlling for CUSIP fixed effects and expected auction sizes. We find that a higher cheapness is associated with a higher auction price markup. A one standard deviation increase in the cheapness measure (across auctions and CUSIPs) increases the bond price markup by 6.3 cents per $100 par value. The auction price markup also has significant positive loadings on volatility and specialness, implying that both the winner's curse and scarcity increase the auction cost. A one standard deviation increase in volatility and specialness increases bond price markup by 3.8 cents and 2.1 cents, respectively (again per $100 par value).

Our main results on the determinants of auction costs are robust to the exact time at which the costs are measured, the universe of bonds included in the yield-curve-fitting

[4]See http://www.federalreserve.gov/pubs/feds/2006/200628/200628abs.html.

model, the yield-curve-fitting model itself, and time-series controls such as yield and yield volatilities, demonstrated in a series of robustness checks.

Because the cost to the Federal Reserve is the profit of primary dealers, we characterize dealers' profitability next. Taking advantage of dealer identities in our proprietary dataset, we reveal the granular heterogeneity of profitability across primary dealers in participating in QE auctions. We measure a dealer's profit margin as the prices of accepted offers less the secondary market prices closest to the auction time, weighted by accepted quantities. Among the 20 primary dealers that participated in QE auctions, the top five have large sale amounts and high profit margins (1.67 cents per \$100 par value on average), while the bottom few dealers sell similarly large amounts but receive negative profit margins (−0.44 cents per \$100 par value on average).

Given the importance of bond cheapness in determining auction costs, we naturally conjecture that the heterogeneity in dealers' profit margin is driven, at least partly, by the heterogeneity in their ability to sell bonds that are deemed cheaper by the Fed. For instance, it would be the case if some dealers had better information of the Fed's yield curve model. Alternatively, some dealers may simply be better at finding those bonds. To investigate the source of the heterogeneity in dealers' profit margin, we run panel regressions of profit margins on cheapness, volatility, and specialness, measured for each winning dealer in each auction. Consistent with the above conjecture, we find that a dealer's profit margin has a significant and positive loading on bond cheapness. A one standard deviation increase in a bond's cheapness (across auction and dealer) increases the auction price markup by 3.8 cents per \$100 par value. Dealers' profit margins also have a positive and significant loading on specialness, and a negative and significant loading on outstanding balance. Together, this evidence suggests that dealers who make more money do so by selling bonds that are deemed cheaper by the Fed or are more costly to locate or finance (more special and lower outstanding balance).

We caution that our results do not make any policy prescription on the optimal repurchase mechanism. The Fed pays a higher cost on bonds that appear cheaper relative to model-implied bond prices, but it is precisely on those "undervalued" bonds that the gains from trade between the Fed and the market are likely the largest. Moreover, as we discuss later, the auction costs seem modest in comparison with Treasury issuance auctions, suggesting that auction is a reasonable, if not perfect, mechanism for implementing quantitative easing.

To the best of our knowledge, this paper provides the first empirical analysis of the *implementation mechanism* of quantitative easing, hence complementing a large literature on the effect of quantitative easing on interest rates (see 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), Li and Wei (2013), D'Amico and King (2013), Meaning and Zhu (2011), and Eser and Schwaab (2016), among others).

The paper most closely related to our work is Han, Longstaff, and Merrill (2007), who analyze the Treasury's buyback auctions of long-term securities 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. We argue that the transparency of the QE auction mechanism is partly why the Fed's preference becomes predictable, which is, in turn, linked to auction costs. 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 and link it to the Fed's relative valuation, a unique economic channel of QE auctions.

More recently, Pasquariello, Roush, and Vega (2014) study how the Fed's open market operations in normal times affect the Treasury market microstructure, using only the purchase amount. We differ by focusing on the auction implementation of unconventional monetary policy, and by using detailed offer-level data of primary dealers.

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.[5] QE auctions differ in that each auction involves multiple substitutable CUSIPs, whereas each issuance auction has one CUSIP at a time. We show how the market seems to take advantage of the relative valuations of multiple CUSIPs by the Fed. Moreover, prior studies of issuance auctions either do not have dealer identities or only have masked identifiers, whereas our data include dealer identities on each CUSIP in each auction, allowing us to study the heterogeneity of dealers' profitability.

[5]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.

2 Institutional Background of QE Auctions

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. (We discuss our data and choice of sample period in Section 4.) These auctions cover two Fed programs. The first, commonly referred to as 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.[6] 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).

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.[7]

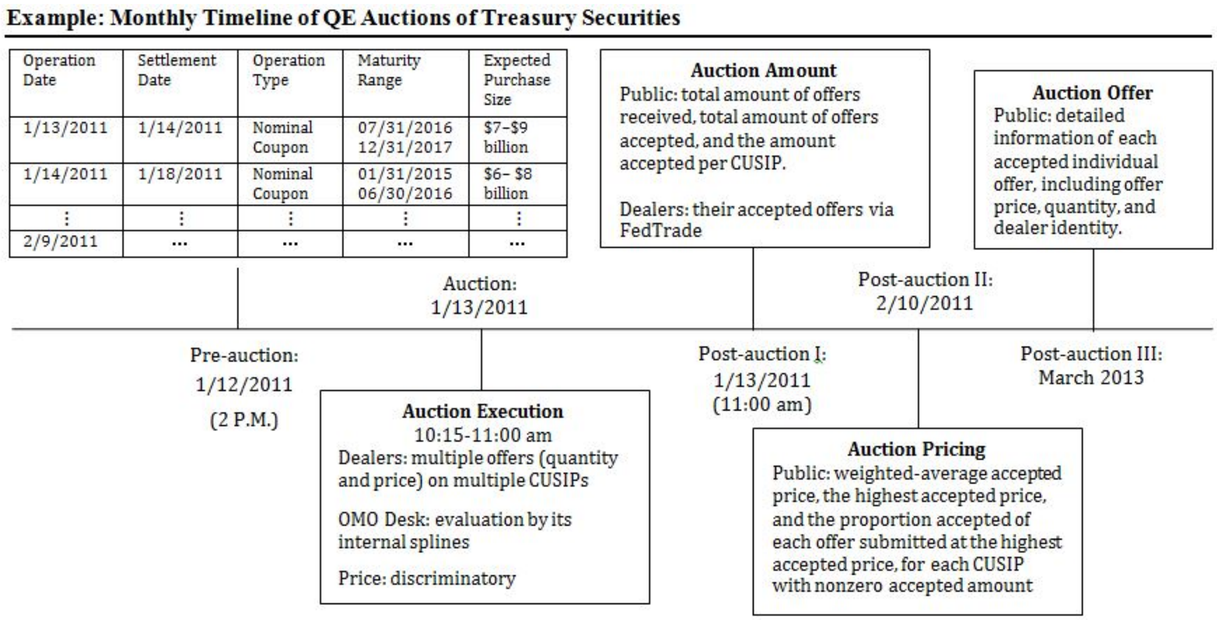
Figure 1 describes the timeline of a typical QE auction, including pre-auction announcement, auction execution, and post-auction information release. To initiate the asset purchase operation, the Fed makes a pre-auction announcement on or around the eighth business day of each month. The announcement 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.[8] Most importantly, this announcement also includes a schedule of anticipated Trea-

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

[7]In the first half of our sample period until February, 2, 2011, there were 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 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. See the website of the Federal Reserve Bank of New York for the historical list of primary dealers.

[8]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

Figure 1: Example of Timeline of QE Auctions



sury 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 par 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.

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. Very rarely, the auctions happen between 10:40am and 11:30am, 11:25am and 12:05pm, and 1:15pm and 2:00pm. Out of the 139 auctions we analyze, one is closed at 11:30am, one is closed at 12:05pm, and three are closed at 2pm. The rest 134 auctions are all closed at

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.

11:00am.

Within a few minutes after the closing of the auction, the Fed publishes the auction results 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.

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 the offered price. Since each auction involves a set of heterogeneous securities/CUSIPs, an algorithm is needed to rank offers on different CUSIPs. To make this ranking, the Fed compares each offer with a benchmark price of the bond for that offer calculated from its internal spline-based yield curve model fitted to the secondary market prices of Treasury securities (Sack (2011)). Thus, these spline-based benchmark prices make different CUSIPs perfect substitutes from the Fed's perspective.

Conditional on filling the desired par purchase amount, the Fed would naturally prefer bonds that trade at a discount in the secondary market relative to otherwise similar bonds. This way, the Fed behaves like a long-term buy-and-hold investor. Although the Fed does not publish its spline yield curve model or estimated benchmark prices, we expect sophisticated investors and primary dealers to have some information about the Fed's yield curve algorithm. After all, fitting yield-curve models is a route practice by sophisticated fixed-income investors and dealers for evaluating the relative cheapness or richness of different bonds. Moreover, dealers may gain information about the Fed's relative valuations through years of interaction and by hiring former Fed employees. As we see in the standard auction model of the next section, if dealers have information about the Fed's relative valuations, bonds that appear cheaper to the Fed will incur a higher cost.

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 use the standard theory of single-unit auctions to illustrate how dealers' information about the Fed's yield curve model affects the auction price markup and guide our empirical analysis. Similar approach is employed in empirical studies of Treasury issuance auctions, such as Cammack (1991), Umlauf (1993), Gordy (1999), and Keloharju, Nyborg, and Rydqvist (2005).

Suppose there are N dealers participating in QE auctions. Consider a bond to be purchased by the Fed in QE auctions. Denote dealer i's valuation of the bond by v_i. In general, there are two components in v_i: (i) the common value component that captures the resale value of the bond in the secondary market; and (ii) the private value component that captures a dealer's idiosyncratic cost in obtaining the bond or private information about the bond. In practice, the common-value component is reflected (at least partly) in the secondary market quotes on various electronic trading platforms available to market participants, such as Bloomberg, BrokerTec, eSpeed, and TradeWeb. The private-value component is affected by a dealer's existing inventory, the cost of financing the bonds in the repo markets, and his relationship with customers and other dealers.

One classical implication from the common-value component is the winner's curse problem: because no dealer is absolutely certain about the resale value of a bond, a dealer worries about buying the bonds too expensively or selling it too cheaply. Applied to QE auctions, a more severe winner's curse problem implies that dealers will submit higher offers to the Fed, leading to a higher expected cost of the Fed. For simplicity, we will not formally reproduce this standard argument here (see Cammack (1991), Umlauf (1993), Keloharju, Nyborg, and Rydqvist (2005), and Han, Longstaff, and Merrill (2007) for more discussions). But the winner's curse channel predicts that a higher bond value uncertainty leads to a higher expected cost of the Fed in QE auctions.

Now, let us focus on the private value components. Since the implication from the common value component is clear, we will assume that the dealers' values $\{v_i\}$ for the bond are all private values, i.e., they are i.i.d. with a distribution function $F : [\underline{v}, \bar{v}] \to [0, 1]$. Note that "i.i.d." should be interpreted as conditional i.i.d., where the conditional information is the common value that depends on the information available to all dealers, such as secondary market price quotes. For simplicity, we normalize the common-value component as zero; this can always be done by shifting the support $[\underline{v}, \bar{v}]$ of $\{v_i\}$.

Suppose that Fed's private valuation for the bond is $v_0 \in [\underline{v}, \bar{v}]$. In the context of QE auctions, v_0 should be interpreted as the relative cheapness of the bond in question, compared to other eligible bonds, based on the Fed's internal spline prices, as discussed in Section 2. Consequently, the multi-object QE auction is equivalent to a single-object auction with the offer prices redefined as the difference between the original offer prices and the Fed's internal spline prices. In this sense, v_0 represents the cheapness of a bond relative to other bonds, based on the Fed's internal spline prices. For reasons discussed before, we expect dealers to have some information about the Fed's relative valuations. Thus, for simplicity, v_0 is assumed to be common knowledge in the model.

Given v_0, among all dealers' offers $\{a_i\}$, the Fed picks the lowest one as long as it is no higher than v_0. If all the offers are higher than v_0, the Fed will not buy this bond. Again, this does not mean that v_0 is the reservation price of the Fed in the usual sense; rather, the interpretation is that if the offer prices on a bond are too high relative to those on other bonds, the Fed will not buy this bond but other bonds. To model the information dealers have on the Fed's yield curve algorithm, we assume that v_0 is common knowledge for simplicity, i.e., dealers have full information on the Fed's preference of bonds. (If dealers only observe a noisy signal of v_0 and hence have a probability distribution over v_0, the qualitative implications of the model do not change.)

We conjecture that a dealer's bidding strategy is a monotone increasing function $\beta(\cdot) : v \mapsto \beta(v)$. Since v_0 is known, a dealer knows she cannot sell the bond at any price higher than v_0. Thus, without loss of generality, we can assume $\beta(v) = v$ if $v \geq v_0$.

Now focus on $v < v_0$. Dealer i wins the auction if $a_N < \min_{j \neq i} \beta(v_j)$, which happens with probability $[1 - F(\beta^{-1}(a_i))]^{N-1}$. So, dealer i's expected profit is

$$\Pi_i = (a_i - v_i)[1 - F(\beta^{-1}(a_i))]^{N-1}. \tag{1}$$

By the standard first-order condition, we can solve

$$\beta(v) = v + \frac{\int_{u=v}^{v_0} (1 - F(u))^{N-1} du}{(1 - F(v))^{N-1}}, \quad v \in [\underline{v}, v_0]. \tag{2}$$

Under this strategy, if the Fed accepts the best offer, the Fed's cost is $\min_i \beta(v_i)$. Thus, a higher offer $\beta(\cdot)$ implies a higher expected cost to the Fed.

All else equal, $\beta(v)$ is increasing in v_0 for $v \in [\underline{v}, v_0]$, for all finite N. This predicts that the auction price is higher if the Fed's value v_0 of the bond is higher. Intuitively, this is because dealers have market power and behave strategically, which is standard in auction theory. Given the interpretation of v_0 as the relative bond cheapness, this implies that the auction price is higher if the bond looks "cheaper" based on the Fed's spline-implied bond value.

In the subsequent empirical analysis, we will construct a measure of bond "cheapness" to proxy for the dealers' information about the Fed's value v_0. We will also control for the standard winner's curse problem by using a proxy for bond value uncertainty.

4 Data and Summary Statistics

In this section, we describe the data and basic summary statistics of the outcomes of QE auctions. Summary statistics include the characteristics of bonds covered in QE auctions, auction size, number of winning offers, and number of winning dealers.

4.1 Data

Our sample period is from November 12, 2010 to September 9, 2011. We focus on this sample period mainly because this is the only QE period during which the Fed purchased only Treasury securities and for which the detailed data of dealer offers are available. Specifically, 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 with a two-year delay after each quarterly operation period. In consequence, detailed dealer offers are available from July 22, 2010. We discard the period July 22, 2010–November 11, 2010 because no orderly expected purchase sizes at the auction level were announced by the Fed in this period. Moreover, on September 21, 2011, the Fed announced the Maturity Extension Program and changes in the agency debt and agency MBS reinvestment policy, which lead to purchases of agency MBS and sales of short-term Treasury securities in addition to purchases of long-term Treasury securities thereafter. Therefore, to avoid potential compounding effects due to other policy operations, we discard the period starting from September 21, 2011 to focus on a "clean" period of only Treasury bond purchases, In addition, we discard the period September 10, 2011–September 20, 2011 because the monthly planned operation of this September is interrupted by the policy change on September 21, 2011.

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 in terms of par value. 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 each of 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 datasets 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 value offered, and the total par value accepted for each auction; (2) the indicator of whether a CUSIP was included or excluded in the auctions; (3) for bonds included in the auctions, the par value accepted, the weighted average accepted price, and the least favorable accepted price for each CUSIP in each auction; and (4) the offered par value, 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.[9]

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). There are four pairs of bid and ask quotes each

[9] 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).

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. We choose these NPQS quotes because the these data cover off-the-run securities that are targeted in QE auctions. (By contrast, the BrokerTec data used in recent studies such as Fleming and Mizrach (2009) and Engle, Fleming, Ghysels, and Nguyen (2012) mainly contain prices of newly issued on-the-run securities.) Moreover, these price quotes are important sources for the Fed's internal spline algorithm and benchmark prices. Hence, our bond cheapness measure using NPQS prices as inputs is probably correlated with the Fed's true preference. Strictly speaking, it would be even better to have higher-frequency price quotes throughout the day, but such data are unavailable to us.

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); D'Amico, Fan, and Kitsul (2013)). We also obtain the outstanding par value of Treasury securities each day from the Monthly Statement of the Public Debt (MSPD) of the Treasury Department.

4.2 Summary Statistics: Bonds Covered in QE Auctions

What Treasury securities does the Fed 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 has an average duration of between 5 and 6 years for the securities purchased. The Fed does not purchase Treasury bills, STRIPS, or securities traded in the when-issued market.[10]

Panel A of Table 2 presents descriptive statistics on the number of bonds for the 139 QE auctions (of nominal Treasury securities) in our sample period. 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

[10]See http://www.newyorkfed.org/markets/lttreas_faq_101103.html for details.

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 shows 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.

13 and 34, averaging 25 per auction. Among these included bonds, in each auction the Fed purchases between 2 and 26 bonds, with an average of 14 bonds. On average, in each auction, 11 eligible bonds are not purchased by the Fed. Across all 139 auctions, only 186 CUSIPs have ever been purchased by the Fed, among the 215 eligible CUSIPs.

According to the Fed's communications to the public, excluded bonds are those trading with heightened specialness in the repo market, or the cheapest to deliver into the front-month Treasury futures contracts.[11] Presumably, these bonds are excluded to avoid creating or 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 as follows:

$$ln[I_{tj}/(1-I_{tj})] = \sum_t \alpha_t D_t + \beta_1 \cdot Specialenss_{tj} + \beta_2 \cdot Maturity_{tj} + \beta_3 \cdot CP_j + \epsilon_{it}, \quad (3)$$

where I_{tj} is the probability of bond j being included in the t-th auction, $Maturity_{tj}$ is the time to maturity measured in years, and CP_j is the coupon rate in percentage points. Because our objective here is to check what type of bonds the Fed includes in an auction, we include auction fixed effects D_t.

Panel B of Table 2 reports the results from the panel Logit regression (3), as well as regressions with only one of $Specialenss_{tj}$, $Maturity_{tj}$, and CP_j on the right-hand side. We

[11]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.

Table 2: Summary Statistics of Bonds in QE Auctions

A: Number of Bonds in QE Auctions					
	Eligible Bonds	Excluded Bonds	Included Bonds	Included Bonds (not purchased)	Included Bonds (purchased)
Mean	26	1	25	11	15
Std	6	1	6	7	5
Min	15	0	13	0	3
Q-25%	20	1	19	5	12
Q-50%	27	1	26	9	15
Q-75%	31	2	29	16	19
Max	36	4	34	28	27

B: Regression of Inclusion Dummy				
Maturity	-0.078**			-0.066**
	(-3.445)			(-2.837)
CP		0.072		0.072
		(1.374)		(1.393)
Specialness			-7.376**	-7.639*
			(-2.683)	(-2.554)
N	3,127	3,127	3,127	3,127
R^2	0.030	0.030	0.054	0.058
Auction FE	Yes	Yes	Yes	Yes

Note: Panel A of this table presents descriptive statistics, including mean, standard deviation (std), minimum (min), maximum (max), and quartiles of the number of bonds covered in the 139 QE auctions of nominal Treasury securities, from November 12, 2010 to September 9, 2011. Panel B reports panel Logit regressions of whether a bond is included in an auction (yes=1, no=0), with z-statistics in the parentheses. The auction fixed effects are included. The right-hand variables are Specialness of a bond (the general repo rate minus special repo rate on the bond) in percentage points, the coupon rate CP in percentage points, and the Maturity in years. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^{+}$ for $p < 0.1$, where p is the p-value.

observe that the regression coefficient of Specialness is significantly negative, confirming that the Fed did exclude bonds trading at heightened specialness. Moreover, the Fed also tends to exclude bonds with longer maturity on average, which is intuitive because, for a fixed auction and hence a maturity bucket, longer-maturity bonds tend to be closer to on-the-run.

4.3 Summary Statistics: Auction Size, Offer, and Dealer

In this section, we present summary statistics of the auction size, number of winning offers, and number winning dealers. Panel A of Table 3 shows that the par amounts of submitted

Table 3: Auction Size, Offer, and Dealer

A: Auction Size							
	Offer Amount ($ billion)	Purchase Amount ($ billion)	Offer to Cover Ratio	Announced Min Size ($ billion)	Announced Max Size ($ billion)	Offer Amount per Included Bond ($ billion)	Purchase Amount per Accepted Bond ($ billion)
Mean	20.76	5.59	4.22	4.58	6.2	0.84	0.41
Std	8.81	2.33	2.87	1.98	2.48	0.31	0.29
Min	4.13	0.72	1.67	0.50	1	0.12	0.04
Q - 25%	13.53	3.16	3.06	2.75	3.5	0.59	0.23
Q - 50%	21.04	6.68	3.66	5	7	0.83	0.36
Q - 75%	27.70	7.30	4.64	6	8	1.05	0.52
Max	42.88	8.87	26.18	7	9	1.76	2.57

B: Number of Winning Offers and Dealers				
	Number of Winning Offers	Number of Winning Dealers	Purchase Amount Per Winning Offer	Purchase Amount Per Winning Dealer
Mean	103	16	0.07	0.36
Std	54	3	0.06	0.17
Min	8	4	0.01	0.06
Q - 25%	57	15	0.04	0.24
Q - 50%	102	17	0.05	0.38
Q - 75%	137	18	0.08	0.45
Max	326	20	0.49	1.38

Note: This table presents descriptive statistics on the auction size (in Panel A) and the number of winning offers and dealers (in Panel B) for the 139 QE auctions of nominal Treasury securities, from November 12, 2010 to September 9, 2011. We report mean, standard deviation (Std), minimum (Min), Maximum (Max), and quartiles at the auction level.

offers vary between \$4 and \$43 billion, averaging about \$21 billion per auction, while the offer amount 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 (offer-to-cover) is on average 4.2, with a range of 1.7 to 26.2. The average expected minimum and maximum auction sizes are \$4.6 billion and \$6.2 billion, and the accepted offer amount always falls between the expected minimum and maximum auction sizes. In addition, the offer amount per included bond is \$0.84 billion on average, while the accepted offer amount per accepted bond is \$0.41 billion.

Panel B of Table 3 presents summary statistics on the number of winning offers and dealers. We observe that the number of winning 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. (In our sample period, the total number of primary dealers was 18 before February 2, 2011 and 20 afterwards.) As a result, per auction, each winning offer has an average size of \$0.07 billion, and each winning dealer sells \$0.36 billion to the Fed on average.

5 Empirical Results

In this section, we present our empirical findings on the costs of the Federal Reserve in executing QE auctions and their economic determinants. We first present summary statistics of the auction costs and then study what economic channels affect auction costs, across bonds as well as across dealers, using panel regressions.

5.1 How Much Does the Fed Pay?

Following the literature,[12] we measure the auction cost as the auction price markup, namely the difference between the auction price and secondary market price on the days the auctions are executed.[13] Let $p_{t,j,d,o}$ and $q_{t,j,d,o}$ be the o-th winning offer price and par value from dealer d on CUSIP j in auction t, respectively, and let $P_{t,j}$ be the secondary market price of the

[12] See, for example, Han, Longstaff, and Merrill (2007), Cammack (1991), Nyborg and Sundaresan (1996), and Hortacsu and Kastl (2012), among others.

[13] We also measure the cost of purchasing a bond as the difference between the worst 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.

CUSIP j at the time auction t is closed. Then the auction price markup of auction t is

$$Markup_t = \frac{\sum_{j,d,o} (p_{t,j,d,o} - P_{t,j}) \cdot q_{t,j,d,o}}{\sum_{j,d,o} q_{t,j,d,o}} \tag{4}$$

That is, the auction price markup 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.

Which secondary-market prices do we use for $P_{t,j}$? Ideally, we would want secondary market prices at the moment the auction is closed, but the NPQS data only provide bid and ask prices at 8:40am, 11:30am, 2:15pm, and 3:30pm. In our sample, 134 of the 139 auctions are closed at 11:00am. Given the data limitation, we use the 11:30am ask price as $P_{t,j}$ for auctions closing at 11:00am, 11:30am, and 12:05pm, and use the 2:15pm ask price for auctions closing at 2:00pm. We refer to these ask prices as the "Closest Ask" because they are as close to the auction-closing times as possible in our data.

Using the Closest Ask, we compute the auction price markup based on (4), denoted $Markup_t^c$. The time gap between auction closing and price quotes implies that, for the vast majority of the auctions, $Markup_t^c$ measures the "realized cost" of the Fed 30 minutes after the auction, which can be interpreted as the profit of dealers by selling the bonds to the Fed in the auction and then covering their short positions in the secondary market 30 minutes later. In addition, for all auctions, we compute the price markup using the 2:15pm ask price and the 3:30pm ask price. In a similar interpretation, the cost measure relative to the 3:30pm ask price, labeled $Markup_t^{3:30pm}$, is the Fed's realized cost 4.5 hours after the auction. Realized costs constructed this way are standard measures in market microstructure (see Hasbrouck (2007)).

Table 4 presents summary statistics of the auction cost $Markup_t$, 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 cents measured relative to the Closest Ask, 2.73 cents relative to the 2:15pm Ask, and 2.15 cents relative to the 3:30pm Ask in the secondary Treasury market. To put the magnitude of $Markup_t$ into perspective, the weighted average bid-ask spread for the purchased bonds (weighted by the par value purchased) is 2.56 cents per \$100 par value during our sample period. Therefore, the average QE auction cost is below or comparable to the average bid-ask spread. These results suggest that the Fed does not suffer large market-impact costs in purchasing the huge amount (\$780 billion) of Treasury securities in QE auctions in our sample period.

Table 4: Auction Cost

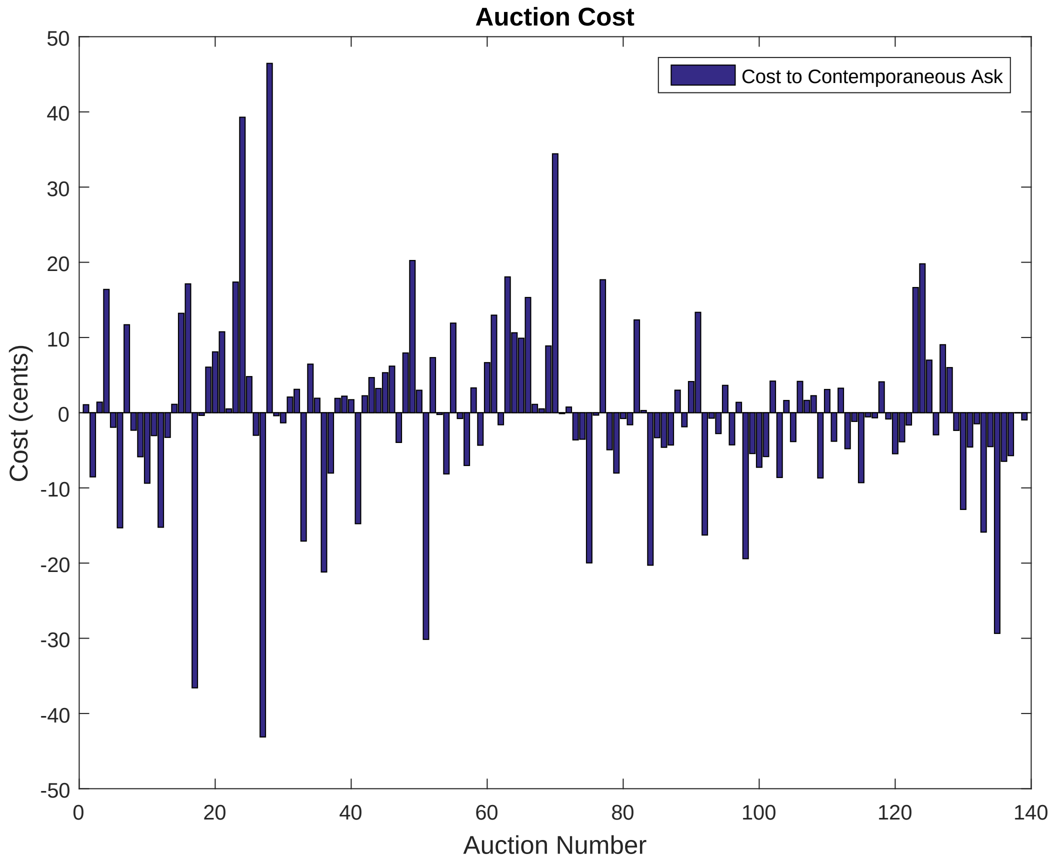
	Quantity-Weighted Mean	Quantity-Weighted Standard Deviation	Min	Max
Cost to Closest Ask	0.71	11.05	-43.12	46.46
Cost to 2:15 PM Ask	2.73	21.89	-92.08	79.19
Cost to 3:30 PM Ask	2.15	26.50	-125.13	102.74

Note: This table presents summary statistics of the auction cost (in cents per $100 par value) to the Fed in the 139 QE auctions from November 12, 2010 to September 9, 2011. The auction cost (auction price markup) is computed as 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 the Closest Ask, the 2:15pm ask, and the 3:30pm ask, as well as the average of the last two as the secondary market price. Closest Ask of a bond equals the 11:30am secondary market ask price for the auctions closed at 11:00am, 11:30am, 12:05pm, and the 2:15pm ask price for the auctions closed at 2:00pm. The quantity-weighted mean and standard deviation are computed as the mean and standard deviation of the auction price markup across the 139 QE auctions, weighted by auction sizes.

It is also informative to compare the QE auction cost to the costs reported in the literature of other Treasury security auctions. Han, Longstaff, and Merrill (2007) report that the Treasury's buyback auctions from March 2000 to April 2002 incur an average cost of 4.38 cents per $100 par value, which is about 70% of the average bid-ask spread of the auctioned bonds. Given that the average par value per auction of these buyback operations is $1.5 billion, which is only about 1/3 of the $5.6 billion (from Table 3) in the QE auctions, the Fed's QE auction mechanism seems to be comparable to the Treasury's buyback auction mechanism in executing large purchases effectively. 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.

While the average auction cost may appear moderate, the aggregate dollar cost is significant, $55 million at 0.71 cents per $100 par value and 213 million at 2.73 cents per $100 par value. Moreover, the variation in costs across auctions is substantially larger. Figure 2 shows that $Markup_t^c$ is strongly time-varying. Across the 139 QE auctions, the minimum and maximum of $Markup_t^c$ are -43.12 cents and 46.46 cents per $100 par value, respectively. Table 4 reports that the quantity-weighted standard deviations of the QE auction price markup is 11.05 cents per $100 par value, if measured relative to the Closest Ask. This

Figure 2: Time Series of Auction Cost



Note: This figure presents the time series of the auction cost (in cents per $100 par value) to the Fed in the 139 QE auctions from November 12, 2010 to September 9, 2011. The auction cost (auction price markup) is computed as the average, weighted by the amount of each accepted offer, of the differences between the offer price and the corresponding Closest Ask of the bond for that offer. Closest Ask of a bond equals the 11:30am secondary market ask price for auctions closed at 11:00am, 11:30am, 12:05pm, and the 2:15pm ask price for auctions closed at 2:00pm.

standard deviation is 26.5 cents per $100 par value, if the cost is measured relative to the 3:30pm ask prices. These large variations of the auction price markup naturally leads to the question of what economic channels drive them, which we investigate in the next subsection.

5.2 What Determines Auction Costs?

We now study the economic drivers of the variations in QE auction costs.

5.2.1 Empirical Measures

As suggested by the stylized model in Section 3, we expect the Fed to pay a higher cost on bonds whose market prices appear lower than prices implied by the Fed's internal yield curve model.

A perfect measure of bond cheapness (from the Fed's perspective) requires full knowledge of the exact method used by the Fed to evaluate offers. We do not have such information. Nonetheless, we will construct a proxy of bond cheapness by applying a popular yield-fitting model to the NYQS data. Specifically, on each auction day, we first estimate a smooth zero-coupon yield curve based on observed market prices. This yield curve is then used to price all bonds purchased in the auction on the auction day. A bond's cheapness is calculated as its theoretical price based on our fitted yield curve minus the market ask price. Noise in this measurement makes it less likely for us to find statistically significant results.

Following Gurkaynak, Sack, and Wright (2007) and Hu, Pan, and Wang (2013), we use the Svensson (1994) functional form of the yield curve, which is an extension of Nelson and Siegel (1987). The Svensson (1994) model assumes the following specification of the instantaneous forward rate:

$$f(m) = \beta_0 + \beta_1 \exp\left(-\frac{m}{\tau_1}\right) + \beta_2 \frac{m}{\tau_1} \exp\left(-\frac{m}{\tau_1}\right) + \beta_3 \frac{m}{\tau_2} \exp\left(-\frac{m}{\tau_2}\right), \tag{5}$$

where m is the time to maturity, and β_0, β_1, β_2, β_3, τ_1, and τ_2 are parameters to be estimated. These parameters must satisfy certain regularity conditions, including $\beta_0 > 0$, $\beta_0 + \beta_1 > 0$, $\tau_1 > 0$, and $\tau_2 > 0$. See Svensson (1994), Gurkaynak, Sack, and Wright (2007), and Hu, Pan, and Wang (2013) for details on the interpretations of these parameters in terms of the yield curve.

For each set of parameters, $\theta \equiv (\beta_0, \beta_1, \beta_2, \beta_3, \tau_1, \tau_2)$, we compute the corresponding zero-coupon yield curve by integrating the forward rates based on (5), which can then be used to price any outstanding Treasury security with specific coupon rates and maturity dates. To estimate the yield curve, we choose the parameters to minimize the weighted sum of the squared deviations between the actual market prices of Treasury securities and the Svensson model implied prices, with the weights chosen as the inverse of the duration of each individual bond. Specifically, let P_t^j be the market price of the bond j available on auction day t, $j = 1, \cdots, N_t$. We choose the parameter θ as

$$\theta_t = \arg\min_{\theta} \sum_{j=1}^{N_t} \left[\left(P_t^j(\theta) - P_t^j \right) / D_t^j \right]^2, \tag{6}$$

where $P_t^j(\theta)$ is the model-implied price of bond j based on the Svensson model in (5), and D_t^j is the bond duration. With the parameter estimate θ_t, we can compute the model-implied price as $P_t^j(\theta_t)$ and define the bond cheapness as

$$Cheapness_t^j = P_t^j(\theta_t) - P_t^j, \tag{7}$$

in unit of cents per \$100 par value. The higher is $Cheapness_t^j$, the lower the raw market price is relative to the theoretical price based on the model estimated using secondary bond prices, and the cheaper the bond j is according to its quoted market price.

We include in the estimation all outstanding Treasury securities in general, but exclude those with maturity less than one month. The yields on ultra-short-maturity Treasury bills may reflect idiosyncratic supply or demand fluctuations beyond the risk-free rate (see Hu, Pan, and Wang (2013) and Gurkaynak, Sack, and Wright (2007)). We also exclude the most recently issued "on-the-run" securities because they are usually excluded in QE auctions to avoid creating supply shortage. But we do include "first off-the-run" bonds (i.e., bonds that are the second most recently issued in their maturity buckets) because they are eligible for QE purchases. The market prices we use are the mid-quotes at 8:40am. By construction, the 8:40am prices are obtained before the auction time and hence not affected by the auction outcomes. (In the robustness section, we construct alternative measures of cheapness and find similar results.)

Although we do not observe the Fed's confidential yield curve model or dealers' information about it, we expect our bond cheapness measure to be positively correlated with that obtained using the Fed's model and the dealers', for two reasons. First, the Svensson (1994) model is a standard model in fixed income markets. Second, our data on secondary market prices are obtained from the Fed, and we expect dealers to observe them as well. We caution that correlated measures do not mean identical measures. We expect some difference among our cheapness measure, the Fed's, and the dealers' because of different sampling time of the data and the exact set of securities included in the yield-fitting calculation, among others.

Turning to other measures, as mentioned in Section 3, a standard determinant of bidding behavior is winner's curse, which in our context could be proxied by the uncertainty of the resale value of the bonds in secondary market. For example, if a dealer sells some bonds to the Fed, anticipating to cover the short position in the secondary market later, a higher bond value uncertainty makes this short-covering trade riskier. Thus, we expect that a higher bond value uncertainty corresponds to a higher cost of the Fed. Following the literature, we measure bond value uncertainty by the pre-auction volatility VOL_t^j, computed as the standard deviation of daily returns of bond j during the five trading days prior to the auction date t.

Besides cheapness and volatility, we also consider three measures of bond scarcity and illiqudity: specialness, outstanding balance, and bid-ask spread. Specialness is the difference between the general repo rate and special repo rate on the CUSIP, in percentage points. The higher is specialness, the more costly it is for a dealer to locate or finance the bond in the repo market. Following Han, Longstaff, and Merrill (2007), we define outstanding balance (OB_t^j) as the total outstanding par value of the bond j, normalized by the total purchase amount of auction t, to control for the potential proportionality of auction size to the outstanding amount. Bid-ask spread ($Bid - Ask_t^j$) is the difference between the ask and bid quotes of bond j, normalized by the mid-quote, denoted in basis points. We use the 8:40am NPQS quotes when computing bid-ask spread, similar to the calculation of cheapness.

Panel A of Table 5 reports basic summary statistics of these five empirical measures across both auctions and CUSIPs. We observe that the purchased bonds by the Fed are on average cheaper than the yield-curve implied value by 25.6 cents per $100 par value, with a standard deviation of 37.5 cents and median of 12.9 cents. The average daily pre-auction volatility is 0.37%, and the average specialness is 2.4 basis points. The mean of (normalized) outstanding balance is 4.99, suggesting that the purchase amount of QE auctions is about 1/5 of the outstanding balance on average. The average bid-ask spread is about 3.5 basis points for the bonds purchased by the Fed.

Panel B of Table 5 reports the correlation matrix of these five empirical measures, pooled across all auctions and CUSIPs. Panel C reports the average time-series correlation matrix by first calculating the correlation for each CUSIP and then averaging across all CUSIPs. Either way, these five explanatory variables have fairly low correlations in their absolute values. The only entry whose absolute value is above 0.4 is the correlation between volatility and normalized outstanding balance, at 0.55. While we do not expect multicollinearity issues for this reason, in our subsequent regressions we will also run univariate versions just in case.

In Panel D of Table 5 we report the time-series correlations of the daily 2-, 5-, 10-, and 30-year par yields from our fitted Svensson yield curve with the corresponding par

Table 5: Summary Statistics of Empirical Measures

A: Basic Summary Statistics across Auctions and CUSIPs					
	Cheapness	VOL	Specialness	OB	Bid-Ask
Mean	25.621	0.369	0.024	4.991	3.522
Standard Deviation	37.533	0.232	0.027	4.202	1.635
Min	-22.668	0.027	-0.027	0.521	0.732
Q - 25%	0.937	0.218	0.009	2.813	2.309
Q - 50%	12.927	0.324	0.016	4.465	3.042
Q - 75%	35.807	0.456	0.030	6.087	4.599
Max	150.682	1.430	0.356	58.806	9.208
B: Pooled Correlations of Empirical Measures					
Cheapness	1.000				
VOL	-0.169	1.000			
Specialness	-0.047	0.087	1.000		
OB	-0.016	0.181	-0.042	1.000	
Bid-Ask	-0.197	0.354	0.172	-0.242	1.000
C: Average Time Series Correlations of Empirical Measures					
Cheapness	1.000				
VOL	-0.081	1.000			
Specialness	0.113	0.185	1.000		
OB	0.184	0.548	0.244	1.000	
Bid-Ask	0.119	0.253	-0.193	-0.123	1.000
D: Yield Curve Correlations with Barclays and GSW					
	2y	5y	10y	20y	30y
Barclays	0.987	0.992	0.989	0.984	0.979
GSW	0.986	0.992	0.992	0.986	0.981

Note: Panel A reports basic summary statistics of five empirical measures, computed across auctions and CUSIPs. For each bond in each auction, Cheapness is the difference between the model price implied from the fitted Svensson yield curve and the actual market mid price (in cents per $100 dollar face value), VOL is the standard deviation of daily returns of the bond during the five trading days prior to the auction date (in percentage points), Specialness is the difference between the general repo rate and special repo rate on the bond (in percentage points), OB is the total outstanding par value of the bond normalized by the total purchase amount of the auction, and Bid-Ask is the difference between the secondary market ask and bid quotes of a bond normalized by the mid-quote (in basis points). Panel B reports the correlation matrix of these five empirical measures by pooling observations across auctions and CUSIPs. Panel C reports their average time series correlations: a correlation between two measures is computed by first calculating their sample correlation across auctions for each CUSIP and then averaging across all CUSIPs. Panel D reports time series correlations of the daily 2-, 5-, 10-, and 30-year par yields from our fitted Svensson yield curve with those from Barclays as well as from Gurkaynak, Sack, and Wright (2007) (GSW) over our sample period.

yields obtained from Barclays and those from Gurkaynak, Sack, and Wright (2007). The correlations are very high, around 0.98 or 0.99. These high correlations provide suggestive evidence that the cheapness measure from our yield curve model is probably correlated with that from the Fed's or dealers' yield curve models.

5.2.2 Regression Results

We now study how the QE auction cost depends on bond cheapness, bond value uncertainty, and bond scarcity/illiquidity. Our main left-hand variable is the auction price markup measured to the Closest Ask, but we will also use the price markup relative to the 3:30pm ask price as a robustness check. For each bond j in each auction t, the CUSIP-level markup is defined as

$$Markup_{t,j} = \frac{\sum_{d,o} (p_{t,j,d,o} - P_{t,j}) \cdot q_{t,j,d,o}}{\sum_{d,o} q_{t,j,d,o}}, \tag{8}$$

where $P_{t,j}$ is either the Closest Ask or the 3:30pm Ask.

Our empirical analysis is based on the following panel regression of the auction cost for each bond in each auction on empirical measures of bond cheapness, value uncertainty, and scarcity/illiquidity:

$$\begin{aligned} Markup_{t,j} &= \sum_j \alpha_j D_j + \beta_1 \cdot \text{Cheapness}_{tj} + \beta_2 \cdot \text{VOL}_{tj} \\ &\quad + \beta_3 \cdot \text{Specialness}_{tj} + \beta_4 \cdot \text{OB}_{tj} + \beta_5 \cdot \text{Bid-Ask}_{tj} \\ &\quad + \beta_6 \cdot \text{Size}_t^E + \epsilon_{it}, \end{aligned} \tag{9}$$

where CUSIP fixed effect D_j controls for potential unobservable effects generic to individual bonds. We do not include auction fixed effects because our main objective is to study the variations of costs across auctions, similar to the literature (such as Han, Longstaff, and Merrill (2007), Nyborg and Sundaresan (1996), and Hortacsu and Kastl (2012), among others). Nonetheless, in order to control for the potential effect of the publicly announced auction size, we include the expected per-CUSIP purchase size Size_t^E, computed as the mean of the announced minimum and maximum of intended purchase amount divided by the number of included CUSIPs, in \$billions of par value.[14]

Columns (1)–(5) of Table 6 report results of panel regressions of the auction price markup

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

relative to Closest Ask, $\text{Markup}^c_{t,j}$, on the empirical measures of bond cheapness, value uncertainty, and scarcity/illiquidity, one at a time. We find that, indeed, cheapness affects the auction price markup positively, consistent with our hypothesis that a higher Fed's value for the bonds (relative to market price) is associated with a higher cost. The auction price markup also has significant and positive loadings on volatility, specialness, and outstanding balance, implying that bond value uncertainty and bond scarcity/illiquidity increase auction costs. The result in Column (6) on the multivariate panel regression (9) further confirms the significance of cheapness, volatility, and specialness (outstanding balance and bid-ask spread become insignificant).

The economic significance of cheapness is particularly large. According to column (6), a 37.5 cents increase in cheapness, which is roughly one standard deviation of cheapness across auctions and CUSIPs in our sample, increases the auction price markup by about 6.3 cents ($= 37.5 \times 0.169$) per \$100 par value. In comparison, a 0.232 and 0.027 percentage point increase in volatility and specialness, which are roughly one standard deviation of the pre-auction volatility and specialness across auction and CUSIP in our sample, respectively, increases the auction price markup by about 3.8 cents ($= 0.232 \times 16.5$) and 2.1 cents ($= 0.027 \times 78.5$) per \$100 par value.

The estimates shown in column (7), without CUSIP fixed effects, are still statistically significant, albeit smaller. Interestingly, as shown in column (8) of Table 6, the magnitudes of the estimated coefficients are larger if the cost is measured against the 3:30pm Ask.

5.3 Dealer Profitability

The cost to the Federal Reserve is the profit of primary dealers. In this subsection, we study the granular heterogeneity of profitability across primary dealers in participating in QE auctions, taking advantage of the availability of dealer identities for each accepted offer in our proprietary dataset.

For each dealer d, we compute his aggregate profit as

$$\text{Aggregate Profit}_d = \sum_{t,j,o} (p_{t,j,d,o} - P_{i,j}) \cdot q_{t,j,d,o}, \tag{10}$$

and profit margin as

$$\text{Margin}_d = \frac{\sum_{t,j,o} (p_{t,j,d,o} - P_{i,j}) \cdot q_{t,j,d,o}}{\sum_{t,j,o} q_{t,j,d,o}}, \tag{11}$$

where we use the Closest Ask for the secondary market price $P_{t,j}$ for CUSIP j and auction

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

Explanatory Variables	(1) Markup^c	(2) Markup^c	(3) Markup^c	(4) Markup^c	(5) Markup^c	(6) Markup^c	(7) Markup^c	(8) $\text{Markup}^{3:30}$
Cheapness	0.201**					0.169**	0.055**	0.218*
	(4.165)					(3.160)	(2.898)	(2.438)
VOL		17.530**				16.534**	1.448	23.453**
		(5.226)				(4.996)	(0.600)	(3.655)
Specialness			58.607**			78.490**	27.270**	172.699**
			(3.365)			(4.556)	(2.841)	(4.169)
OB				-0.115*		-0.018	-0.093^+	-0.056
				(-2.282)		(-0.342)	(-1.946)	(-0.690)
Bid-Ask					-0.347	-0.716	-0.349	-0.744
					(-0.615)	(-1.276)	(-1.535)	(-0.642)
Size^E						2.137	1.737^+	-2.028
						(1.240)	(1.659)	(-1.496)
N	1,776	1,776	1,776	1,776	1,776	1,776	1,776	1,776
R^2	0.103	0.114	0.092	0.086	0.086	0.139	0.015	0.129
CUSIP FE	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

Note: This table reports results of panel regressions of the auction price markup, for each purchased bond in each of the 139 QE auctions of nominal Treasury securities executed from November 12, 2010 to September 9, 2011. The auction price markup $\text{Markup}^c_{t,j}$ is computed as the average, weighted by the amount of each accepted offer, of the differences between the offer price and the corresponding Contemporaneous Ask (the 11:30am secondary market ask price for auctions closed at 11:00am, 11:30am, 12:05pm, and the 2:15pm ask price for auctions closed at 2:00pm) of the bond for that offer. $\text{Markup}^{3:30}_{t,j}$ is measured relative to the 3:30pm ask price. For each bond in each auction, Cheapness is the difference between the model price implied from the fitted Svensson yield curve and the actual market mid price (in cents per $100 dollar face value), VOL is the standard deviation of daily returns of the bond during the five trading days prior to the auction date (in percentage points), Specialness is the difference between the general repo rate and special repo rate on the bond (in percentage points), OB is the total outstanding par value of the bond normalized by the total purchase amount of the auction, and Bid-Ask is the difference between the secondary market ask and bid quotes of a bond normalized by the mid-quote (in basis points). Expected Auction Size is computed as the mean of the announced minimum and maximum of the total auction amount to be purchased divided by the number of included CUSIPs in $billions of par value. Robust t-statistics that correct for serial correlation in the residuals clustered at the CUSIP level are reported in parentheses. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^+$ for $p < 0.1$, where p is the p-value.

t.

Table 7 summarizes the dealer-by-dealer profitability across the 139 QE auctions in our sample period. Column (1) lists the rankings according to dealers' aggregate profits, while the dealer identities are provided in column (2). Columns (3), (4), and (5) provide the aggregate profit in millions of dollars, the profit margin in cents per $100 par value, and the aggregate accepted offer amount in billion dollars of par value, respectively. In addition, we also report the total number of auctions in column (6), the number of winning offers per auction in column (7), and the total number of CUSIPs sold in column (8).

From columns (3)–(5), we observe a striking concentration of aggregate profits and aggregate amounts of accepted offers among dealers. The top five dealers, Morgan Stanley, Goldman Sachs, BNP Paribas, J.P. Morgan, and RBC make a combined profit of $59 million, even larger than the $55.37 million total profit of all dealers, measured relative to the Closest Ask. These five dealers also accounted for about half the $776.6 billion total purchase amount. Furthermore, the bottom five dealers, RBS, Credit Suisse, UBS, Barclays Capital, and Citigroup accounted for about 40% of the $776.6 billion total purchase amount, but their profit margins are much lower. In fact, the bottom five dealers all have negative profit margins, averaging about -0.44 cents per $100 par value, whereas the top five dealers all have positive profit margins, averaging 1.67 cents per $100 par value.

In sum, during QE auctions, the intermediation profits in the Treasury market is concentrated to only a few dealers. Similar concentration has been documented in other over-the-counter markets such as municipal bond, corporate bond, and asset-backed securities (Li and Schurhoff (2014), Di-Maggio, Kermani, and Song (2016), and Hollifield, Neklyudov, and Spatt (2014)). Furthermore, there is substantial heterogeneity in the profit margins among dealers who handle similar amounts of intermediation volume. Hence, dealers' profit margins in QE auctions seem to be related to economic channels that are orthogonal to their sales volume.

To link dealers' profitability to our empirical measures of the determinants of auction costs, we ask to what extent dealer's profit margin depends on the dealer's ability to sell to the Fed bonds that are cheaper (relative to model), more volatile, or more special. To do this, we run the following panel regression at the auction-dealer level:

$$\begin{aligned}\text{Margin}_{t,d} &= \sum_d \alpha_d D_d + \beta_1 \cdot \text{Cheapness}_{t,d} + \beta_2 \cdot \text{VOL}_{t,d} \\ &\quad + \beta_3 \cdot \text{Specialness}_{t,d} + \beta_4 \cdot \text{OB}_{t,d} + \beta_5 \cdot \text{Bid-Ask}_{t,d} \\ &\quad + \beta_6 \cdot \text{Size}^E_t + \epsilon_{it}, \qquad (12)\end{aligned}$$

Table 7: Dealer Profitability

(1) Rank by Aggregate Profit	(2) Dealer Identity	(3) Aggregate Profit ($ million)	(4) Profit Margin (Cents per $ 100)	(5) Aggregate offer amount ($ billion)	(6) Total Number of Auctions	(7) Number of Winning Offers per Auction	(8) Total Number of Winning CUSIPs
1	Morgan Stanley	22.67	1.80	125.88	128	6	129
2	Goldman Sachs	19.30	1.34	143.61	138	12	147
3	BNP Paribasl	7.61	1.57	48.49	131	32	174
4	J.P. Morgan	6.45	1.96	32.91	131	5	137
5	RBC	2.97	1.66	17.92	103	4	127
6	Merrill Lynch	2.26	1.35	16.78	114	5	130
7	Daiwa	1.77	2.04	8.71	89	3	81
8	HSBC	1.67	0.74	22.55	117	3	114
9	Jefferies	1.22	0.94	12.92	116	3	108
10	Nomura	0.68	0.36	19.08	116	3	117
11	Deutsche Bank	0.57	0.24	24.24	113	5	125
12	Cantor Fitzgerald	0.36	0.62	5.80	101	3	96
13	Mizuho	-0.19	-0.41	4.74	90	3	80
14	SG Americas	-0.21	-0.56	3.77	51	2	45
15	MF Global	-0.34	-1.53	2.21	40	2	44
16	RBS	-0.63	-0.11	59.27	120	5	120
17	Credit Suisse	-0.72	-0.09	82.97	132	6	140
18	UBS	-0.8	-0.31	25.61	106	4	117
19	Barclays Capita	-2.77	-0.4	69.57	131	7	144
20	Citigroup	-6.50	-1.31	49.61	124	5	135
Average		2.77	0.50	38.83	110	6	116

Note: This table summarizes the dealer profitability across the 139 QE auctions of nominal Treasury securities from November 12, 2010 to September 9, 2011. 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 Closest Ask (the 11:30am secondary market ask price for the auctions closed at 11:00am, 11:30am, 12:05pm, and the 2:15pm ask price for the auctions closed at 2:00pm) for the bond of that offer, for each dealer across all auctions. The aggregate profit of each dealer is computed as the product between the profit margin and total offer amount the dealer sold to the Fed. We rank the dealers according to their aggregate profits, and report the corresponding rankings, dealer identities, aggregate profits in $ millions, profit margins in cents per $100 par value, aggregate offer amount in $ billions of par value sold to the Fed, total number of auctions, number of winning offers per auction, and total number of CUSIPs sold.

where the profit margin $\text{Margin}_{t,d}$ of dealer d in auction t is computed as

$$\text{Margin}_{t,d} = \frac{\sum_{j,o} (p_{t,j,d,o} - P_{i,j}) \cdot q_{t,j,d,o}}{\sum_{j,o} q_{t,j,d,o}}, \tag{13}$$

and the secondary market price $P_{t,j}$ for CUSIP j of auction t is the Closest Ask. In regression (12), the empirical measures $\text{Cheapness}_{t,d}$, $\text{VOL}_{t,d}$, $\text{Specialness}_{t,d}$, $\text{OB}_{t,d}$, and $\text{Bid-Ask}_{t,d}$ are calculated as the average of the respective measures of each purchased CUSIP for each winning dealer d in each auction t, weighted by this dealer's purchase amount of this CUSIP in auction t. Therefore, $\text{Cheapness}_{t,d}$ measures the average cheapness of the bonds dealer d sold to the Fed in auction t, and similarly for other measures. We include the dealer fixed effect D_d to control for potential unobservable effects generic to dealers, but do not include auction fixed effects because our main objective is to study the variations of costs across auctions, similar to (9). We also control for the potential auction size effect by including the expected per-CUSIP auction size Size_t^E.

Literally, the coefficient β_1 reflects the degree of heterogeneity in the average cheapness of the bonds that different dealers sell to the Fed. Similar interpretations apply to the other coefficients.

Table 8 reports the results. In columns (1)–(6), the univariate and multivariate regressions show that the dealer profit margin $\text{Margin}_{t,d}^c$ is significantly higher if the dealer-specific cheapness measure is higher. In particular, from column (6), a 29 cent per \$100 par value increase in cheapness, which is roughly one standard deviation of cheapness *across auction and dealer* in our sample, increases the dealer's profit margin by about 3.8 cents ($= 29 \times 0.132$) per \$100 par value. A 0.022 percentage point increase in specialness, which is roughly one standard deviation of specialness across auctions and dealers in our sample, increase the dealer's profit margin by about 0.63 cents ($= 0.022 \times 28.451$) per \$100 par value. The coefficient for volatility, however, is insignificant.

Columns (7) and (8) show robustness of the main results. Interestingly, the estimates in column (7), where dealer fixed effects are excluded from the right-hand side, are almost identical to those in column (6). In column (8), where costs are measured relative to the 3:30pm Ask, the coefficient for cheapness remains significant, albeit smaller.

Table 8: Panel Regression of Dealer Profitability across Dealer/Auction

Explanatory Variables	(1) $\text{Margin}^c_{t,d}$	(2) $\text{Margin}^c_{t,d}$	(3) $\text{Margin}^c_{t,d}$	(4) $\text{Margin}^c_{t,d}$	(5) $\text{Margin}^c_{t,d}$	(6) $\text{Margin}^c_{t,d}$	(7) $\text{Margin}^c_{t,d}$	(8) $\text{Margin}^{3:30}_{t,d}$
Cheapness	0.132**					0.132**	0.132**	0.026$^+$
	(6.600)					(6.716)	(6.909)	(1.928)
VOL		1.476$^+$				-1.167	-1.331	1.840
		(1.786)				(-0.987)	(-1.219)	(0.850)
Specialness			42.046**			28.451**	30.183**	35.360*
			(4.174)			(2.957)	(3.211)	(2.800)
OB				-0.113**		-0.078**	-0.081**	-0.118**
				(-3.175)		(-4.119)	(-4.685)	(-3.030)
Bid-Ask					-4.476**	1.974	2.149	-6.409*
					(-2.907)	(0.645)	(0.756)	(-2.254)
Size^E						0.035	-0.011	0.422
						(0.170)	(-0.053)	(1.520)
N	1,720	1,720	1,720	1,720	1,720	1,720	1,720	1,720
R^2	0.037	0.005	0.011	0.006	0.007	0.043	0.040	0.017
Dealer FE	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

Note: This table reports results of panel regressions of the dealer profit margin, for each winning dealer in each of the 139 QE auctions of nominal Treasury securities executed from November 12, 2010 to September 9, 2011. The dealer profit margin $\text{Margin}^c_{t,d}$ is computed as the average of the differences between the offer price and the corresponding Contemporaneous Ask (the 11:30am secondary market ask price for the auctions closed at 11:00am, 11:30am, 12:05pm, and the 2:15pm ask price for the auctions closed at 2:00pm) of all purchased CUSIPs for each winning dealer d in each auction t, weighted by this dealer's purchase amount on the corresponding CUSIP in auction t, while $\text{Markup}^{3:30}_{t,j}$ is measured relative to the 3:30pm ask price. The explanatory variables, $\text{Cheapness}_{t,d}$, $\text{VOL}_{t,d}$, $\text{Specialness}_{t,d}$, $\text{OB}_{t,d}$, and $\text{Bid-Ask}_{t,d}$ are calculated similarly. For each bond in each auction, Cheapness is the difference between the model price implied from the fitted Svensson yield curve and the actual market mid price (in cents per $100 dollar par value), VOL is the standard deviation of daily returns of the bond during the five trading days prior to the auction date (in percentage points), Specialness is the difference between the general repo rate and special repo rate on the bond (in percentage points), OB is the total outstanding par value of the bond normalized by the total purchase amount of the auction, and Bid-Ask is the difference between the secondary market ask and bid quotes of a bond normalized by the mid-quote (in basis points). Expected Auction Size is computed as the mean of the announced minimum and maximum of the total auction amount to be purchased divided by the number of included CUSIPs in $billions of par value. Robust t-statistics that correct for serial correlation in the residuals clustered at the dealer level are reported in parentheses. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^+$ for $p < 0.1$, where p is the p-value.

6 Additional Results and Robustness

In this section, we provide additional results and robustness checks on our main empirical finding of the determinants of QE auction costs.

6.1 Controlling for Purchase Amount

As mentioned before, our measure of auction costs are realized costs–purchase price at auction time minus market prices some time after the auction. One may suspect that the auction outcome itself may affect the measured cost by affecting the secondary market prices after the auction. To mitigate this concern, we explicitly control for the effect of published quantity by adding $q_{11am,j,d,o}$ to our baseline regression (9). Columns (1)-(6) of Table 9 report these regression results. We observe that cheapness, volatility, and specialness all remain highly significant, with similar magnitude as in the baseline specification. Moreover, column (7) reports the regression of the auction purchase quantity on the same set of explanatory variables. We observe no significant loadings on cheapness and specialness, suggesting that the Fed does not purchase more bonds that look cheaper or more special. But there is a positive loading on volatility and a negative loading on bid-ask spread. Overall, our main results on the economic determinants of auction costs are robust to the slightly lagged timing of the auction price markup measure.[15]

6.2 Alternative Cheapness Measures

Recall from equation (7) that our baseline bond cheapness measure is $Cheapness_t^j = P_t^j(\theta_t) - P_t^j$, where $P_t^j(\theta_t)$ is the theoretical price based on the Svensson model estimated using all available bond (mid) prices, and P_t^j is the market price. We now provide evidence on the robustness of our main results to alternative measures of bond cheapness.

First of all, since $Cheapness_t^j$ is measured in cents per \$100 par value, it may be mechanically larger in magnitude for expensive bonds such as long-term bonds with high coupon rates. To alleviate this concern, we construct two alternative measures of bond cheapness. The first normalizes $Cheapness_t^j$ by the market price P_t^j, while the second transforms the prices P_t^j and $P_t^j(\theta_t)$ into par yields and then takes the yield difference. Columns (1)-(4) of Table 10 report results of our main regression (9) using these two alternative measures of bond cheapness. Both univariate and multivariate regressions confirm the results in the

[15]We are grateful to Stefania D'Amico for pointing out these potential issues.

Table 9: Regressions Including Purchase Amount

Explanatory Variables	(1) Markup^c	(2) Markup^c	(3) Markup^c	(4) Markup^c	(5) Markup^c	(6) Markup^c	(7) q
Cheapness	0.168**					0.134*	-0.008
	(3.492)					(2.535)	(-0.393)
VOL		17.391**				16.591**	6.159**
		(5.178)				(4.992)	(3.195)
Specialness			58.757**			77.859**	-0.987
			(3.341)			(4.502)	(-0.102)
OB				-0.138*		-0.040	0.279^+
				(-2.558)		(-0.684)	(1.956)
Bid-Ask					-0.298	-0.591	-0.852**
					(-0.522)	(-1.040)	(-3.248)
q	0.056	0.048	0.067	0.076^+	0.065	0.045	
	(1.341)	(1.173)	(1.522)	(1.735)	(1.470)	(1.052)	
Size^E						2.226	1.341
						(1.268)	(1.635)
N	1,776	1,776	1,776	1,776	1,776	1,776	1,776
R^2	0.102	0.114	0.093	0.088	0.087	0.137	0.069
CUSIP FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: This table reports results of panel regressions of the auction price markup and purchase amount, for each purchased bond in each of the 139 QE auctions of nominal Treasury securities executed from November 12, 2010 to September 9, 2011. The auction price markup $\text{Markup}^c_{t,j}$ is computed as the average, weighted by the amount of each accepted offer, of the differences between the offer price and the corresponding Contemporaneous Ask (the 11:30am secondary market ask price for auctions closed at 11:00am, 11:30am, 12:05pm, and the 2:15pm ask price for auctions closed at 2:00pm) of the bond for that offer. For each bond in each auction, Cheapness is the difference between the model price implied from the fitted Svensson yield curve and the actual market mid price (in cents per $100 dollar face value), VOL is the standard deviation of daily returns of the bond during the five trading days prior to the auction date (in percentage points), Specialness is the difference between the general repo rate and special repo rate on the bond (in percentage points), OB is the total outstanding par value of the bond normalized by the total purchase amount of the auction, Bid-Ask is the difference between the secondary market ask and bid quotes of a bond normalized by the mid-quote (in basis points), and q is the purchase amount normalized by the total auction amount (in percentage points). Expected Auction Size is computed as the mean of the announced minimum and maximum of the total auction amount to be purchased divided by the number of included CUSIPs in $billions of par value. Robust t-statistics that correct for serial correlation in the residuals clustered at the CUSIP level are reported in parentheses. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and + for $p < 0.1$, where p is the p-value.

baseline specification.

Second, we compute $Cheapness_t^j$ using alternative inputs of secondary market bond prices in fitting the Svensson model, including ask prices (instead of mid prices), all bonds with maturities longer than a year (instead of all bonds except those on-the-run or with maturity less than a month), and the 3:30pm bond prices one day before the auction (instead of bond prices at 8:40am on the auction day). Columns (5)-(10) of Table 10 report results of the main regression (9) using these three alternative measures. We find the results to be similar to the baseline specification.

Third, we compute $Cheapness_t^j$ using a spline method (i.e. piecewise-defined polynomials) with a roughness penalty function of Fisher, Nychka, and Zervos (1995) that balances the goodness-of-fit and the smoothness of the forward yield curve. Columns (11)-(12) of Table 10 report results of the main regression (9) using the spline-based bond cheapness measure. Again, the results are similar to the baseline specification.

6.3 Time Series Controls

As discussed in Section 5.2.2, our baseline regression (9) controls for the expected per-CUSIP purchase size. One may be concerned that other time-series variations, such as those in interest rates and interest rate volatilities, can drive variations of auction costs over time. For example, Figure 2 seems to suggest that the variations in auction costs may be decreasing over time.

We conduct a robustness check by including, as control variables, 2-year, 5-year, and 10-year zero-coupon Treasury yields, denoted y(2), y(5), and y(10), as well as at-the-money swaption implied volatilities of 2-year, 5-year, and 10-year swap rates, denoted SIV(2), SIV(5), and SIV(10). The series of zero-coupon yields are from Gurkaynak, Sack, and Wright (2007), whereas those of three-month swaption implied volatilities are from Barclays. The results are reported in Table 11. As before, we find that the coefficients for cheapness, volatility, and specialness remains similar to the baseline specification.

Table 10: Alternative Measures of Cheapness

Explanatory	Normalized		Yield Based		Ask Based		Maturity $\geq$ 1y		Previous Day		Spline Based	
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Cheapness	0.17**	0.14*	0.96**	0.80**	0.17**	0.14**	0.10**	0.08*	0.20**	0.17**	0.19**	0.18*
	(3.53)	(2.59)	(4.44)	(3.34)	(3.92)	(2.89)	(3.30)	(2.55)	(4.80)	(3.74)	(3.24)	(2.58)
VOL		16.68**		17.53**		16.53**		17.98**		16.37**		6.59
		(5.02)		(5.32)		(4.89)		(5.48)		(4.89)		(1.64)
Specialness		77.85**		78.15**		77.25**		79.15**		77.32**		61.71**
		(4.54)		(4.53)		(4.49)		(4.58)		(4.44)		(3.73)
OB		-0.03		-0.02		-0.02		-0.05		-0.01		0.01
		(-0.47)		(-0.43)		(-0.43)		(-0.96)		(-0.27)		(0.32)
Bid-Ask		-0.63		-0.57		-0.58		-0.38		-0.73		0.02
		(-1.11)		(-1.01)		(-1.04)		(-0.68)		(-1.26)		(0.04)
Size^E		2.21		1.90		2.22		2.37		2.15		1.21
		(1.26)		(1.17)		(1.27)		(1.27)		(1.24)		(0.98)
N	1,776	1,776	1,776	1,776	1,776	1,776	1,776	1,776	1,761	1,761	1,776	1,776
R^2	0.10	0.14	0.10	0.14	0.10	0.14	0.09	0.13	0.11	0.14	0.11	0.12
CUSIP FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: This table reports results of panel regressions of the auction price markup, for each purchased bond in each of the 139 QE auctions of nominal Treasury securities executed from November 12, 2010 to September 9, 2011. The auction price markup $\text{Markup}^c_{t,j}$ is computed as the average, weighted by the amount of each accepted offer, of the differences between the offer price and the corresponding Contemporaneous Ask (the 11:30am secondary market ask price for auctions closed at 11:00am, 11:30am, 12:05pm, and the 2:15pm ask price for auctions closed at 2:00pm) of the bond for that offer. For each bond in each auction, Cheapness is the difference between the model price implied from a fitted yield curve model and the actual market mid price (in cents per $100 dollar face value), VOL is the standard deviation of daily returns of the bond during the five trading days prior to the auction date (in percentage points), Specialness is the difference between the general repo rate and special repo rate on the bond (in percentage points), OB is the total outstanding par value of the bond normalized by the total purchase amount of the auction, and Bid-Ask is the difference between the secondary market ask and bid quotes of a bond normalized by the mid-quote (in basis points). Expected Auction Size is computed as the mean of the announced minimum and maximum of the total auction amount to be purchased divided by the number of included CUSIPs in $billions of par value. Different versions of Cheapness are included, including the difference between the model price and market price normalized by the market price ("Normalized"), the difference between the par yields of the market and model prices ("Yield-Based"), the measure by fitting the curve using ask prices ("Ask Based"), the measure by fitting the curve using the bonds with maturities larger than a year ("Maturity $\geq$ 1y"), the measure by fitting the curve using the bond price quotes one day before the auction ("Previous Day"), and the measure by fitting the curve using spline model ("Spine Based"). Robust t-statistics that correct for serial correlation in the residuals clustered at the CUSIP level are reported in parentheses. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and + for $p < 0.1$, where p is the p-value.

Table 11: Time Series Controls

Explanatory Variables	(1) $Markup^c$	(2) $Markup^c$	(3) $Markup^c$	(4) $Markup^c$	(5) $Markup^c$	(6) $Markup^c$	(7) $Markup^c$
Cheapness	0.178**	0.170*	0.187**	0.183**	0.189**	0.193**	0.171*
	(2.773)	(2.482)	(2.865)	(2.635)	(2.848)	(2.817)	(2.592)
VOL		15.564**		15.083**		12.916**	15.871**
		(3.496)		(3.196)		(2.793)	(3.744)
Specialness		52.227**		55.077**		55.574**	48.354**
		(3.213)		(3.365)		(3.418)	(2.954)
$Size^E$	1.144	0.456	1.209^+	0.391	1.122	0.242	0.440
	(1.599)	(0.553)	(1.709)	(0.502)	(1.630)	(0.338)	(0.506)
y(2)	7.550**	7.929**					57.688**
	(2.989)	(3.115)					(3.401)
SIV(2)	-6.585**	-12.397**					-24.322**
	(-2.625)	(-4.869)					(-3.837)
y(5)			2.577*	1.763			-39.906**
			(2.401)	(1.636)			(-3.943)
SIV(5)			-5.350	-17.979**			6.509
			(-1.078)	(-3.621)			(0.460)
y(10)					2.907*	1.919^+	17.882**
					(2.478)	(1.695)	(3.943)
SIV(10)					-6.007	-21.144**	-4.811
					(-0.782)	(-2.838)	(-0.408)
N	1,757	1,757	1,757	1,757	1,757	1,757	1,757
R^2	0.135	0.151	0.129	0.144	0.129	0.142	0.168
CUSIP FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: This table reports panel regressions of the auction price markup, for each purchased bond in each of the 139 QE auctions of nominal Treasury securities executed from November 12, 2010 to September 9, 2011. The auction price markup $\text{Markup}^c_{t,j}$ is computed as the average, weighted by the amount of each accepted offer, of the differences between the offer price and the corresponding Contemporaneous Ask (the 11:30am secondary market ask price for auctions closed at 11:00am, 11:30am, 12:05pm, and the 2:15pm ask price for auctions closed at 2:00pm) of the bond for that offer. For each bond in each auction, Cheapness is the difference between the model price implied from the fitted Svensson yield curve and the actual market mid price (in cents per $100 dollar face value), VOL is the standard deviation of daily returns of the bond during the five trading days prior to the auction date (in percentage points), and Specialness is the difference between the general repo rate and special repo rate on the bond (in percentage points). Expected Auction Size is computed as the mean of the announced minimum and maximum of the total auction amount to be purchased divided by the number of included CUSIPs in $billions of par value. The 2-, 5-, and 10-year Treasury yields (y(2), y(5), and y(10), respectively) as well as three-month swaption implied volatilities on 2-, 5-, and 10-year swap rates (SIV (2), SIV (5), and SIV (10), respectively) are included as controls. Robust t-statistics that correct for serial correlation in the residuals clustered at the CUSIP level are reported in parentheses. Significance levels: ** for $p < 0.01$, * for $p < 0.05$, and $^+$ for $p < 0.1$, where p is the p-value.

7 Conclusion

Since the global financial crisis, central banks around the world have implemented aggressive quantitative easing. This paper provides the first empirical analysis of QE auctions, the unique mechanism that implements QE in the U.S. Treasury markets. A unique feature of QE auctions, relative to issuance auctions, is that the Fed evaluates offers on multiple, substitutable bonds based on internal benchmark prices. The transparency of such mechanism makes the Fed's relative values partly predictable.

In our sample period of November 2010 to September 2011, the Federal Reserve purchased $780 billion Treasury securities. Using a proprietary dataset that contains details of each winning offer in each QE auction, we find that the Fed pays 0.71–2.73 cents per $100 par value above the secondary market ask prices. We further show that the cost of buying a bond in QE auctions has a significant and economically large loading on bond "cheapness"—how much the bond market price is below a yield-curve-model-implied value. A higher volatility or specialness is also associated with a higher cost. Moreover, we find great heterogeneity of profit margins across dealers with comparable selling amounts. Our evidence suggests that dealers seem to have information about the relative valuations of the Fed on multiple bonds.

A possible direction of future research is to consider possible improvement of QE auctions, or study the optimal mechanism for implementing QE purchases. This direction remains highly relevant to the extent that central banks may continue using QE in the future. One approach is to estimate dealers' supply curves and conduct counterfactual analysis of alternative auction design. But such an analysis is likely to require data on dealers' offers that are rejected by the Fed, which we do not have. We thus leave this task for future research.

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