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Abstract

We provide evidence that the ECB's unconventional monetary policy dampens yield cycles in secondary Eurozone sovereign debt markets around new sovereign debt auctions. This effect increases in market volatility. Cycles caused by domestic auctions and the role of market volatility are largest for countries with low credit ratings. Auctions by these countries generate highly-significant auction cycles in other countries. Auction cycles can have a non-negligible effect on debt-servicing costs, but these may be contained by concentrating debt issuance in tranquil periods, and by coordinating auction calendars among countries, so as to maximize the dispersion of auction activity in time.

Keywords: auction cycles, sovereign debt, asset purchase programs, primary market, secondary market, market volatility.
JEL classification: E43, G12, G18, G15.

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1 Introduction

During and following the Eurozone debt crisis the European Central Bank (ECB) was forced to undertake unconventional monetary policy measures. While its net asset purchases have been halted at the moment, monetary policy remains extremely loose. Although the ECB is forbidden to trade in the primary market for public debt and claims not to affect price formation in this market,[1] this paper presents evidence that the sovereign debt purchases by the European System of Central Banks (ESCB) affect servicing costs of new debt by dampening the "auction cycles" in the secondary market for sovereign debt.

The auction cycle hypothesis states that, in the run-up to a new debt auction, yields on outstanding debt with a high pay-off correlation with the instrument on issue rise, while they revert to their original level after the auction.[2] Auction cycles may arise because, prior to a new debt auction, primary dealers have to free up space in their trading portfolios, which they optimally do by reducing their position in instruments closely substitutable to the instrument on auction (i.e. the instruments have a high pay-off correlation). Alternatively, prior to the auction they short highly-substitutable instruments in order to hedge the risk from taking the newly-issued debt on their balance.

We develop a simple theoretical framework that shows how the ESCB sovereign debt purchases may dampen auction cycles by propping up demand for already outstanding highly-substitutable debt around auctions. The model also shows that auction cycles tend to be larger, when market volatility is higher. However, this effect is in turn dampened when ESCB sovereign bond purchases are increased.

Our main empirical findings tend to be in line with our theoretical model. We find strong

[1] In particular, the ECB states that "We do not buy government bonds in the primary market, which is explicitly forbidden under Article 123. And neither do we act in the secondary market in a way which could be perceived as equivalent to acting in the primary market.", see `https://www.ecb.europa.eu/press/key/date/2016/html/sp160623.en.html`

[2] To fix terminology, we refer to a "domestic auction cycle" as the auction cycle in a country's debt resulting from an auction by the country itself and a "foreign auction cycle" as an auction cycle in the country's debt resulting from an auction by *another* country.

evidence of cycles associated with both domestic and foreign auctions. More market volatility magnifies these cycles. Further, we find evidence that larger amounts of central bank sovereign debt purchases tend to dampen both the average size of the cycles associated with domestic and foreign auctions, as well as the positive effect of market volatility on the magnitude of these cycles. We show that domestic auction cycles and the role of market volatility for domestic auction cycles are largest for countries with low credit ratings. Moreover, debt issuance by these countries generates strong cross-border auction cycle effects. Because daily data on ESCB sovereign debt purchases are not publicly available, we carefully construct our purchases data from the monthly balances of the national central banks. Hence, the effects that we estimate with the available data could well be even stronger if higher-frequency data on sovereign debt purchases would be available.

Our estimates indicate that cycles caused by both domestic and foreign debt auctions can have a non-negligible effect on debt-servicing costs and that these costs can be reduced by ESCB sovereign debt purchases. A back-of-the-envelope calculation for France, a country with a relatively low credit rating in our sample, suggests that the domestic (foreign) auction cycle raises debt-servicing costs by over €100 million (5 million) during the lives of the new 10-year bonds issued in a given year. A one-standard deviation increase in market volatility raises these figures by around €120 million (11 million), while typical central bank purchasing behaviour lowers these costs by roughly €25 million and €2 million for the domestic and foreign cycles, respectively.

Our results suggest that Eurozone governments can economize on debt-servicing costs by issuing relatively more debt in tranquil periods and coordinating their auction calendars among themselves. Moreover, if central banks were to time their purchases to periods with high general market volatility average debt-servicing costs may be reduced further. Such a policy might be compatible with the objective of not unduly influencing sovereign debt markets, as purchases would not be linked to the specific timing of the auctions. Further, the dampening effect of the purchases on the auction cycles would be temporary in any case, as yields tend to revert to their original level some days after an auction.

This paper relates to the literature on auction cycles, unconventional monetary policy, and cross-border contagion. Fleming and Rosenberg (2007) and Lou et al. (2013) both find evidence of auction cycles for the United States. Beetsma et al. (2016) confirm the presence of auction cycles for Italian sovereign debt, but not for German sovereign debt. Sigaux (2018) confirms the price fall of the debt during the run-up to Italian treasury auctions. Beetsma et al. (2018) extend Beetsma et al. (2016) by developing a theoretical model that allows for auction cycle effects of foreign debt issuance. For both they find substantial evidence. This paper extends Beetsma et al. (2018) by introducing purchases by the ESCB and by expanding their sample further both in the time and the cross-sectional dimension, allowing us to differentiate between auction cycles of countries with low and high credit ratings. This paper also generalizes the theoretical framework underlying the earlier papers.

A second, related strand of the literature investigates how quantitative easing affects sovereign debt policy. Examples are Krishnamurthy and Vissing-Jorgenson (2011) for the United States and De Santis (2014) for Europe. Afonso et al. (2018) examine the effect of ECB policy on the relationship between bond prices and their fundamental determinants, sovereign risk in particular. Finally, De Santis (2012), Acharya et al. (2014) and Ehrmann and Fratzscher (2017) document (cross-border) contagion of bond markets as an important phenomenon. Broner et al. (2014) present a framework to explore the consequences of EU bond market fragmentation during the crisis, emphasizing shifts of investors towards domestic sovereign debt and the resulting crowding out effects on private investment. However, to the best of our knowledge, this is the first paper exploring how ESCB sovereign debt purchases affect auction cycles and how auction cycles differ with country credit ratings.

The remainder of this paper is organized as follows. In Section 2 we provide information on the organization and design of Eurozone sovereign debt auctions, and the ESCB's asset purchasing programs. Section 3 develops our theoretical framework. In Section 4 we describe our data and the variables used in the empirical analysis. To motivate the empirical analysis, Section 5 presents an event study showing that, prior to an auction, sovereign secondary market yields increase, while after the auction they decrease. Section 6 presents the regression framework and the estimation results. It also provides some back-of-the-envelope calculations for the effect of auction cycles on debt-servicing costs and the influence of ESCB sovereign debt purchases in moderating these costs. Finally, Section 7 concludes the main text.

2 Background Information on Auction Processes and ESCB Asset Purchasing Programs

This section provides some institutional and policy background information of relevance for our analysis. First, we provide a concise description of the Eurozone sovereign bond issuance processes. After that, we discuss the independence and the asset purchasing programs of the ESCB.

2.1 Auctions of Sovereign Debt

In order to finance their budget deficits or to roll over existing debt, governments issue debt at public auctions. Before the start of the year the Debt Management Office (DMO) fixes the auction dates for the coming year, which can be found in the national issuance calendar of the European Union (EU).[3] However, specific details of each auction, such as the maturity and size of the issue(s),[4] are usually disclosed only several days prior to the auction date. Participants in the auctions are the so-called primary dealers. Typically, to limit their risk exposure, in the run-up to the auction they sell instruments in the secondary market that are highly substitutable with the instrument on auction. During the auction they take the newly-issued debt on their books, which in the following days they distribute further in the secondary market. Figure 1 summarizes the events around an auction.

[3] https://europa.eu/efc/national-issuance-information_en

[4] Some countries tend to auction more than one instrument on the same day.

Beginning of year	Announcement of auction dates
Run-up to auction	Announcement of auction size and maturity of debt
	Primary dealers sell substitutable bonds in secondary market
Auction	Primary dealers buy newly-issued debt
Post auction	Primary dealers distribute new debt in secondary market.

Figure 1: Auction Timeline.

Beetsma et al. (2018) notice the large overlap of the primary dealer base across the countries (Belgium, Germany, Spain, France, Italy and the Netherlands) in their dataset. For instance, they observe that six major banks are primary dealer for all the countries in their dataset. Moreover, all the primary dealers of France and the Netherlands are also active as primary dealer for Germany.[5] This network of primary dealer activity may be conducive to the cross-border effects of new debt issues that we allow for in our analysis. In particular, if a primary dealer is active in both countries A and B and the debt of the two countries is highly substitutable, then a new issue of country B debt may induce a primary dealer to reduce its holding of country A debt, thereby driving up the yield on country A debt.

2.2 Independence of the ESCB

To ensure its independence, the ECB has its own capital. A country's contribution to the ECB's capital is based on its "capital key", which is the average of its shares of EU GDP and population. Eurozone national central banks (NCBs) are required to pay their subscriptions in full, while non-Eurozone NCBs only pay 7% of their subscription. When a country joins the Eurozone, the capital keys and paid up capital change.

Not only is the ECB politically and financially independent, it is also prohibited from providing monetary financing, as laid down in Article 123 of the Treaty on the Functioning of the European Union (TFEU).[6] This should incentivize Member States to pursue sound budgetary policies. The Treaty also covers the use of unconventional monetary policy.

[5] Strictly speaking, the German DMO does not use a primary dealer system, but has the so-called "Bund Auction Group" of banks that participate in German debt auctions and to this end fulfill certain requirements. With a slight abuse of terminology, we refer to these banks as "primary dealers".

[6] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:12012E/TXT&from=EN

For instance, to prevent risk-sharing among the Eurozone Member States, unconventional monetary policy measures should be applied to individual Eurozone Member States in accordance with the capital key and sovereign debt purchases are carried out by the NCB of the country that issued the debt. The only grounds for potential deviation from the capital key of NCB sovereign debt purchases are low market liquidity and a binding "issuer limit" (the maximum allowable holdings of each issuer).[7] Otherwise, the NCB completes its purchases up to the point at which its monthly budget is exhausted. In particular, purchasing activity is inelastic to asset price developments.

2.3 The Asset Purchasing Programs

Since the beginning of the European sovereign debt crisis the ECB has launched eight asset purchasing programs (APPs): three covered-bond purchase programs (CBPP1, CBPP2, and CBPP3), the securities markets program (SMP), the outright monetary transactions (OMT) program,[8] the asset-backed securities purchase program (ABSPP), the public sector purchase program (PSPP), and the corporate sector purchase program (CSPP). These programs all count as quantitative easing (QE) policies, except for the SMP and OMT programs, because under these programs purchases are fully sterilized such that the money supply remains unchanged. The sizes and periods during which the programs were or are operational are listed in Table 1. The table also reports the division of the purchases between the primary and secondary markets. Whereas private debt is bought on both the primary and secondary market, public debt is only bought on the latter.[9]

The ECB started buying covered bonds in May 2009 with the CBPP1. The main objective of the program - and of the subsequent programs CBPP2 and CBPP3 starting in November 2011 and October 2014, respectively - was to increase the downward pressure on interbank rates, improve the funding conditions for credit institutions, promote credit provisioning through

[7] https://www.ecb.europa.eu/pub/economic-bulletin/articles/2019/html/ecb.ebart201902_01~3049319b8d.en.html#toc4

[8] Strictly speaking, the OMT is not viewed as an APP as the ESCB never made a purchase under this program.

[9] In these programs purchases are offset by fixed-term loans – see the ECB monthly bulletin of June 2010, https://www.ecb.europa.eu/pub/pdf/other/mb201006_focus01.en.pdf.

these credit institutions, and enhance liquidity in the private debt market. Whereas the minimum credit rating of the debt securities had to be AA under CBPP1, this requirement was lowered to a minimum rating of BBB- under CBPP2 and CBPP3. The novel feature introduced with the CBPP3 was an "issue limit" that restricted the ECB to hold a maximum share of 70% per international securities identification number (ISIN). This issue limit was intended to prevent the ECB from becoming the sole holder of individual instruments. The limit was extended to the securities bought under the CBPP1 and the CBPP2. The CBPP3 was adapted in January 2017 to allow for purchases of assets with a negative yield. The ECB intends to hold the acquired securities until maturity.

Table 1: Dates and Sizes of the Asset Purchasing Programs.

Program	Start	End	Size (blns €)	Sterilized	1st-2nd (%)	
CBPP1	02-07-2009	30-06-2010	60	No	27-73	
SMP	10-05-2010	06-09-2012	218	Yes	0-100	
CBPP2	03-11-2011	31-10-2012	16	No	37-63	
OMT	06-09-2012	-	0	Yes	0-100	
CBPP3	20-10-2014	19-12-2018	262	No	37-63	expanded APP
ABSPP	21-11-2014	19-12-2018	26	No	51-49	expanded APP
PSPP	09-03-2015	19-12-2018	2093	No	0-100	expanded APP
CSPP	08-06-2016	19-12-2018	178	No	18-82	expanded APP

Notes: (i) "1st-2nd (%)" indicates division in percent of purchases between primary and secondary market. (ii) For the programs, "Size" indicates the holdings at the date in the column under "End".

The SMP, which started in May 2010, was the first program in which the ECB targeted sovereign debt securities. The objective of the program was to improve the functioning of the securities markets and to improve the monetary policy transmission mechanism. Purchases were done in the 2- to 10-year secondary markets only, with the intention to hold the assets until maturity. According to Fratzscher et al. (2016), initial purchases consisted of Greek, Irish, and Portuguese government bonds only. From August 2011 onwards, the ECB included Italian and Spanish government bonds in the SMP. By purchasing bonds of countries in financial distress spreads were reduced and the monetary policy transmission mechanism improved. In the beginning of 2012, when market conditions had improved, the

ECB terminated the purchases. At that moment the ECB held €218 bln worth of sovereign debt, making the SMP the third largest asset purchase program of the ECB.

The SMP was terminated in 2012 with the start of the Outright Monetary Transactions (OMT) program. The OMT program is designed to improve the monetary policy transmission mechanism by containing the fear of a Eurozone break-up and the resulting redenomination risk. Even though the ECB can buy in unlimited quantities sovereign debt with a maturity of up to three years, the instrument has not (yet) been used. However, the announcement of the OMT program, during the "Whatever it takes"-speech of ECB President Draghi on the 26^{th} of July 2012, sufficed for sovereign spreads to recede.

As inflation remained low and expected inflation declined, on 22 January 2015 the ECB decided to expand the Eurosystem's balance sheet with quantitative measures under the (expanded) asset purchase programs, which is the collection of programmes under which the ESCB purchases private and public debt. Of the different programs, the PSPP program initiated in March 2015 is by far the largest – around ten times larger than any other program. The initial purchases of sovereign and supranational debt, amounting to €60 bln a month, were made to improve the monetary transmission mechanism and to increase the provision of credit to the real economy. The program was intended to last until inflation had returned to a level consistent with price stability, i.e., close to, but below, 2%. Bonds with a maturity ranging from to two to 30 years are included in the program and redemptions are reinvested. Of the monthly budget 88% is allocated to sovereign debt. The other 12% is spent on bonds issued by international organisations and multilateral development banks. In March 2016 these fractions changed to 90% and 10%, respectively. The purchases are restricted by an "issue limit" and an "issuer limit". The issue limit is the ESCB's maximum allowable holding per ISIN. The limit was initially 25% of the issue's nominal size. In September 2015 this limit was raised to 33%. The issuer limit, aimed at curbing market impact and the risks associated with the ECB becoming the largest creditor of Eurozone governments, so aimed at respecting the prohibition on monetary financing, is the maximum share of an issuer's outstanding securities the ECB is allowed to buy and equals 33% as well.

In June 2016 the monthly purchases were raised to €80 bln with the start of the CSPP. Under this program the ECB buys corporate bonds in both the primary and secondary markets with a maturity ranging from six months to 31 years. The issue limit for purchases of corporate bonds is 70% per ISIN. Again, the purchases were supposed to last until inflation would be close to but below 2%.

In October 2017 the ECB decided to extend the length of the programs and to reduce the monthly purchases to €30 bln from January 2018 onwards. On the 12^{th} of June 2018 ECB president Draghi announced to scale back the monthly purchases to €15 bln, starting in October 2018. The net purchases ended on December 19^{th} 2018.[10] The redemptions of the expiring assets are reinvested at least for some time to come. Aggregate purchases by the ECB amount to over €2.5 trillion worth of assets.

3 The Theoretical Model

This section sets up a model featuring new sovereign debt issues bought by globally and locally active primary dealers. It extends Beetsma et al. (2018), which in turn builds on the asset pricing model of De Jong & Rindi (2009, Ch. 2), by introducing the ESCB as an additional buyer of sovereign debt in the secondary market.[11]

The mechanism driving the auction cycle in our model is the limited risk-bearing capacity of the primary dealers, which is determined by their limited (trading) wealth and their innate risk-aversion. As a result, they demand to be compensated for the risk they run as long as the newly-issued debt is on their books. Hence, prior to the auction the portfolio-optimizing primary dealers free up room in their portfolios by selling in the secondary market public debt

[10] New sovereign debt purchases are in the pipeline. However, these fall outside the sample period of our analysis.

[11] We assume that the ESCB does not directly buy debt in the auction, because sovereign debt purchases under the asset purchasing programs are only allowed to take place in the secondary market – see Table 1.

that is highly substitutable with the debt that is on auction. Not only does this push down secondary market prices, but also the price at which the new debt is acquired, because of its high substitutability with the outstanding debt. In the days after the auction the primary dealers pass the newly-issued debt on to their customers, and the downward pressure on secondary-market prices abates. An essential element of the model is the assumption of partially-segmented markets, which in turn builds on earlier work of Errunza and Losq (1985) and De Jong and De Roon (2005). The assumption allows for spill-overs from foreign auctions onto secondary markets for domestic debt. Another essential element is that demand from the ESCB does not result from portfolio optimization. In particular, it is inelastic to price changes. We will see that this inelasticity alleviates the normal pre-auction downward pressure on prices.

The model in this section features the primary dealers and the ESCB as the only traders of the assets we describe. The primary dealers trade both the newly-issued assets on the primary market and the existing assets on the secondary market. The ESCB trades only existing assets on the secondary market. The Appendix (not for publication) generalizes the setup further by allowing for an additional group of optimizing traders, who are not primary dealer and trade on the secondary market only. Numerical analysis suggests that the results we derive below continue to hold for the extended model.

3.1 Model Setup

There are N risky assets and one risk-free asset. Further, there are two periods, period 0 and period 1. In period 0, the representative primary dealer is endowed with wealth W, which it uses for trading in the market. In period 1, the pay-offs of the assets materialize. The risk-free asset pays a deterministic return of $1 + r_f$, while the vector of gross returns of the risky assets $\tilde{F}$ is for analytical reasons assumed to be multivariate-normally distributed. Denote by the vector $X = \left[X_R^\top, x_{rf}\right]^\top$ the demand for the N risky assets X_R and the risk-free asset x_{rf}. The price of the risk-free asset is normalized to unity. We denote the price vector of the risky assets by P_R. Hence, we can write the primary dealer's period-0 budget constraint as $W = X_R^\top P_R + x_{rf}$. The value of the portfolio in period 1 is stochastic and given by $\tilde{w} = X_R^\top \tilde{F} + \left(W - X_R^\top P_R\right)(1 + r_f)$. The primary dealer maximizes expected utility $\mathbb{E}\left[U(\tilde{w})\right]$ over the portfolio weights, where the function $U(\cdot)$ is strictly concave and twice continuously differentiable. Applying Stein's lemma to the standard first-order conditions,[12] and using some simple algebra, yields:

$$P_R = \frac{1}{1+r_f}\left(\mathbb{E}\left[\tilde{F}\right] + \frac{\mathbb{E}\left[U''(\tilde{w})\right]}{\mathbb{E}\left[U'(\tilde{w})\right]} X_R^\top \Sigma_{\tilde{F}}\right)$$

where $\Sigma_{\tilde{F}}$ is the variance-covariance matrix of the pay-off vector $\tilde{F}$. We assume that $U(\cdot)$ is a function with constant coefficient of absolute risk aversion $\kappa > 0$. Defining $\eta > 0$ as the coefficient of relative risk-aversion, i.e. $W\kappa = \eta$, using that $X_R^\top \Sigma_{\tilde{F}} = \Sigma_{\tilde{F}} X_R$, and assuming without loss of generality that $r_f = 0$, we can write:

$$P_R = \mathbb{E}\left[\tilde{F}\right] - \frac{\eta}{W}\Sigma_{\tilde{F}} X_R \tag{1}$$

We now assume that there are two countries, Home and Foreign. We can split the pay-off vector into the pay-offs on Home (or "domestic", denoted with subscript d) and Foreign (denoted with subscript f) assets, i.e. $\tilde{F} = \left[\tilde{F}_d^\top, \tilde{F}_f^\top\right]^\top$. The variance-covariance matrix of the pay-offs is correspondingly partitioned into:

$$\Sigma_{\tilde{F}} = \begin{bmatrix} \Sigma_{d,d} & \Sigma_{d,f} \\ \Sigma_{d,f}^\top & \Sigma_{f,f} \end{bmatrix}$$

where $\Sigma_{d,d}, \Sigma_{d,f}$ and $\Sigma_{f,f}$ denote the variance-covariance matrix of the domestic bond pay-offs, the matrix of covariances of the pay-offs between domestic and foreign bonds, and the variance-covariance matrix of the foreign bond pay-offs, respectively.

We allow for partially-segmented markets by assuming that there are some "global" primary dealers who trade in all the assets and some "local" primary dealers who trade only risky

[12]Given two continuously-differentiable stochastic variables, X and Y, that are jointly normal, Stein's lemma states that $\mathbb{C}\mathrm{ov}\left[f(X), Y\right] = \mathbb{E}\left[f^{'}(X)\right]\mathbb{C}\mathrm{ov}\left[X, Y\right]$.

assets of either Home or Foreign. This reflects the observation that in practice some primary dealers are active only in a limited set of countries, while others are active in all major economies, see Beetsma et al. (2018, Table 1, page 6). The trading activity of the latter group is a channel for the transmission of the effects of Foreign auction activity onto Home markets. Applying (1) to the local primary dealers, denoted by $c \in \{d, f\}$, and the global primary dealers, denoted by g, their respective demands X_c and $X_g = \left[X_{g,d}^\top, X_{g,f}^\top\right]^\top$ are implicitly given by:

$$
\begin{aligned}
P_c &= \mathbb{E}\left[\tilde{F}_c\right] - \eta W_c^{-1} \Sigma_{c,c} X_c \\
P &= \mathbb{E}\left[\tilde{F}\right] - \eta W_g^{-1} \Sigma X_g
\end{aligned}
$$

where $P = \left[P_d^\top, P_f^\top\right]^\top$ is the partitioning of the price vector into those of domestic and foreign bonds. Rewriting yields:

$$
\begin{aligned}
X_c &= \frac{1}{\eta} W_c \Sigma_{c,c}^{-1} \left(\mathbb{E}\left[\tilde{F}_c\right] - P\right) \\
X_g &= \frac{1}{\eta} W_g \Sigma^{-1} \left(\mathbb{E}\left[\tilde{F}\right] - P\right)
\end{aligned}
\tag{2}
$$

The novel feature of the model is the demand of the ESCB for sovereign bonds. Whereas the primary dealers optimize utility, the demand of the ESCB is assumed to be price-inelastic. The motivation for this assumption is that the objective of its asset purchasing programs is not to maximize the expected return (subject to a risk budget). In fact, the ESCB is committed to buying an amount of assets equal to the allocated budget under the asset purchasing programme. Of course, in their purchasing activities, national central banks have some, but limited, room to "play" with the timing and composition of the instruments bought from the market, depending on market liquidity and the distance to the issue limit. Denote the ESCB's and total demands for domestic and foreign bonds by $\left[X_{E,d}^\top, X_{E,f}^\top\right]^\top$ and $\bar{X} = \left[\bar{X}_d^\top, \bar{X}_f^\top\right]^\top$,[13] respectively. With this notation and equation (2), the aggregate

[13]Due to the ESCB's inactivity in the primary sovereign debt market, $\left[X_{E,d}^\top, X_{E,f}^\top\right]^\top$ can be partitioned further into $\left[\left[X_{E,d,o}^\top, 0\right], \left[X_{E,f,o}^\top, 0\right]\right]^\top$, where $X_{E,d,o}$ and $X_{E,f,o}$ are the ESCB demands of domestic and

demands by the primary dealers are given by:

$$\begin{bmatrix} \bar{X}_d - X_{E,d} \\ \bar{X}_f - X_{E,f} \end{bmatrix} = \frac{1}{\eta} \left(\begin{bmatrix} W_d \Sigma_{d,d}^{-1} & 0 \\ 0 & W_f \Sigma_{f,f}^{-1} \end{bmatrix} + W_g \Sigma^{-1} \right) \left(\mathbb{E}\left[\tilde{F}\right] - P \right)$$

Denote the supply of domestic and foreign bonds by $S = \left(S_d^\top, S_f^\top\right)^\top$. Equating $\bar{X}$ and S, and solving for P, one can write:

$$P = \mathbb{E}\left[\tilde{F}\right] - \eta A^{-1} \Sigma \begin{bmatrix} S_d - X_{E,d} \\ S_f - X_{E,f} \end{bmatrix}$$

with $A \equiv \begin{bmatrix} (W_d + W_g) I & W_f \beta_{d,f} \\ W_d \beta_{f,d} & (W_f + W_g) I \end{bmatrix}$, where $\beta_{d,f} = \Sigma_{d,f} \Sigma_{f,f}^{-1}$ and $\beta_{f,d} = \Sigma_{f,d} \Sigma_{d,d}^{-1}$. Define $B = A^{-1}$. By applying the formulas of Bierens (2014) for the inverse of a partitioned matrix, one can write:

$$\begin{aligned} B_{11} &= \left(A_{11} - A_{12} A_{22}^{-1} A_{21}\right)^{-1} = \left[(W_d + W_g) I - \frac{W_d W_f}{W_f + W_g} \beta_{d,f} \beta_{f,d}\right]^{-1} \\ B_{12} &= -B_{11} A_{12} A_{22}^{-1} = -B_{11} \frac{W_f}{W_f + W_g} \beta_{d,f} \end{aligned}$$

Using these expressions, and solving for domestic bond prices, yields the main pricing equation:

$$\begin{aligned} P_d = \mathbb{E}\left[\tilde{F}_d\right] - \eta \big[W_g I + W_d (I - \theta_f R)\big]^{-1} \Big[&(I - \theta_f R) \Sigma_{d,d} (S_d - X_{E,d}) \\ &+ (I - \theta_f) \Sigma_{d,f} (S_f - X_{E,f}) \Big] \end{aligned} \tag{3}$$

where $\theta_f \equiv W_f / (W_f + W_g)$ is the wealth of the foreign primary dealers relative to that of all the primary dealers (global and local) in foreign debt, and $R \equiv \beta_{d,f} \beta_{f,d} = \Sigma_{d,f} \Sigma_{f,f}^{-1} \Sigma_{f,d} \Sigma_{d,d}^{-1}$. This expression provides the general format for the various cases we investigate below. First, we consider a situation with only two domestic, but no foreign, bonds. One of these is the bond that is auctioned, while the other bond already exists in the secondary market. Second,

foreign debt in the secondary market (the subscript "o" is used to indicate "old" or existing debt), and the zeroes in the vector indicate the zero purchases in the domestic and foreign primary markets.

we examine a situation with a pre-existing domestic and a newly-issued foreign bond.

3.2 The Case of Two Domestic Bonds

This subsection explores the effect of a new domestic sovereign bond issue on the price of an existing "old" domestic bond. Subscript "n" indicates the new bond, "o" the old bond. Since $\theta_f = 0$, equation (3) simplifies to:

$$P_d = \mathbb{E}\begin{bmatrix}\tilde{F}_{d,o} \\ \tilde{F}_{d,n}\end{bmatrix} - \frac{\eta}{W_d + W_g}\begin{bmatrix}\sigma^2_{d,o} & \rho_{o,n}\sigma_{d,o}\sigma_{d,n} \\ \rho_{o,n}\sigma_{d,o}\sigma_{d,n} & \sigma^2_{d,n}\end{bmatrix}\begin{bmatrix}S_{d,o} - X_{E,d,o} \\ S_{d,n} - X_{E,d,n}\end{bmatrix}$$

where $\sigma_{d,o}$ and $\sigma_{d,n}$ denote the standard deviations of the pay-offs $\tilde{F}_{d,o}$ and $\tilde{F}_{d,n}$ of the old, respectively new, bond. The correlation between these pay-offs is denoted by $\rho_{o,n}$. Further, assume that one can write:

$$\begin{bmatrix}\sigma^2_{d,o} & \rho_{o,n}\sigma_{d,o}\sigma_{d,n} \\ \rho_{o,n}\sigma_{d,o}\sigma_{d,n} & \sigma^2_{d,n}\end{bmatrix} \equiv \gamma \begin{bmatrix}\delta^2_{d,o} & \rho_{o,n}\delta_{d,o}\delta_{d,n} \\ \rho_{o,n}\delta_{d,o}\delta_{d,n} & \delta^2_{d,n}\end{bmatrix}$$

where $\gamma > 0$ is the general level of market volatility, in the following simply referred to as "market volatility".

As the precise amounts and dates of the debt purchases by the ESCB are not public, we assume a simple and plausible price-inelastic specification for the demand from the ESCB in the secondary market. Our specification assumes that the amounts bought by the ESCB in the *secondary* market are proportional to the sizes of the new debt issues in the *primary* market. This reflects the fact that both the sizes of the new debt issues and the total country budgets for the ESCB purchases are linked to the size of the country, while, moreover, the ESCB is restricted by the issue and issuer limits and its desire to minimize its influence on the formation of secondary market prices. In most instances, auctions are reopenings of instruments already traded on the secondary market. Hence, when new debt is issued, and existing ESCB holdings of the instrument are already close to the issue limited, room emerges to buy an extra amount of the instrument on the secondary market. Concretely, we specify ESCB demand in the *secondary* market for domestic old debt as $X_{E,d,o} = \alpha S_{d,n}$, where $\alpha > 0$. We obtain:

Result 1.

Suppose that ESCB secondary-market demand for domestic old debt is given by $X_{E,d,o} = \alpha S_{d,n}$*, where* $0 < \alpha < 1$*. Then:*

$$a. \quad \frac{\partial P_{d,o}}{\partial S_{d,n}} = -\frac{\eta}{W_d + W_g}\gamma\left(\rho_{o,n}\delta_{d,o}\delta_{d,n} - \alpha\delta_{d,o}^2\right)$$

$$b. \quad \frac{\partial}{\partial \gamma}\frac{\partial P_{d,o}}{\partial S_{d,n}} = -\frac{\eta}{W_d + W_g}\left(\rho_{o,n}\delta_{d,o}\delta_{d,n} - \alpha\delta_{d,o}^2\right)$$

If α is sufficiently small and the pay-off correlation $\rho_{o,n}$ between old and new bonds is positive and sufficiently large, then $\alpha\delta_{d,o}^2 \leq \rho_{o,n}\delta_{d,o}\delta_{d,n}$. In the following, we assume that this condition is fulfilled. Because our empirical analysis focuses on secondary-market yields of instruments of the same or almost the same maturity as the one on auction, the relevant case for us is the one in which the correlation between the pay-offs of the old and the new instrument is (very) high.[14]

The first expression in Result 1 shows that the size of the new debt issue has a negative effect on the price of the old bond and, hence, a positive effect on its yield. This is what we will refer to as the "domestic auction cycle". It increases in the size of the auction, the correlation $\rho_{o,n}$ between the pay-offs of old and new debt and the risk-aversion of the primary dealers. A higher correlation implies that the old bond has to offer a higher expected return to induce primary dealers to keep it in their portfolios when new debt is issued. The auction cycle decreases if aggregate trading wealth of primary dealers, $W_d + W_g$, increases, because the new debt issue makes up a smaller fraction of their portfolios and, hence, there is less pressure to sell existing debt with positively correlated pay-offs. Further, we observe that a

[14] Also, public debt yields are for a substantial part driven by factors that are common for a given sovereign, such as perceptions of default risk and inflation expectations, thus producing a strong positive correlation in the pay-offs of non-identical instruments issued by the same sovereign.

tightening of the link between the ESCB purchases and the size of the new debt issue, i.e. a higher α, dampens the auction cycle. Finally, under the above condition on α, an increase in market volatility γ magnifies the auction cycle, while a higher value of α dampens this effect of higher market volatility, as can be seen by differentiating the second expression with respect to α.

The condition $\alpha\delta_{d,o}^2 \leq \rho_{o,n}\delta_{d,o}\delta_{d,n}$ may provide additional rationalization why the ESCB imposes restrictions on its holdings of individual instruments. The condition limits the impact of ESCB purchases on asset prices, in that an increase in a country's sovereign debt supply still exerts a downward effect on its secondary-market value. In this sense, the condition limits the ESCB's influence on the "normal" functioning of the sovereign debt markets.

3.3 The Case of One Domestic and One Foreign Bond

Now we turn to the effect of foreign sovereign debt issuance on the price of a domestic bond. Defining $\hat{W} = W_g + W_d\left(1 - \theta_f\rho_{d,f}^2\right)$ as the wealth "effectively" available for investment in domestic debt, equation (3) boils down to:

$$P_d = \mathbb{E}\left[\tilde{F}_d\right] - \frac{\eta}{\hat{W}}\Big[\left(1 - \theta_f\rho_{d,f}^2\right)\sigma_d^2\left(S_d - X_{E,d}\right) + \left(1 - \theta_f\right)\rho_{d,f}\sigma_d\sigma_f\left(S_f - X_{E,f}\right)\Big]$$

where σ_d and σ_f denote the standard deviations of the pay-offs $\tilde{F}_d$ and $\tilde{F}_f$, respectively, and $\rho_{d,f}$ the correlation between these pay-offs. Notice that, even though domestic primary dealers do not directly participate in the foreign auction, through $\hat{W}$ their wealth still affects the price response of the domestic asset. The reason is that the pre-auction sale by the global primary dealers of existing domestic debt can be more easily absorbed by the domestic primary dealers if their wealth is larger. Also, through θ_f the wealth of the foreign primary dealers features in this expression, as their demand for the new foreign debt affects the portfolio demand for the domestic debt. Only if the correlation $\rho_{d,f}$ between the debt pay-offs is zero, does foreign primary dealer wealth no longer affect the portfolio demand for the domestic debt. The analogue to Result 1 is:

Result 2.

Suppose that a foreign debt auction is accompanied by the ESCB buying foreign debt in proportion to the size of the new foreign debt issue, i.e. $X_{E,f} = \alpha S_f$*. Then:*

$$a. \quad \frac{\partial P_d}{\partial S_f} = -\frac{\eta}{\hat{W}}\left(1-\theta_f\right)\rho_{d,f}\gamma\delta_d\delta_f\left(1-\alpha\right)$$

$$b. \quad \frac{\partial}{\partial\gamma}\frac{\partial P_d}{\partial S_f} = -\frac{\eta}{\hat{W}}\left(1-\theta_f\right)\rho_{d,f}\delta_d\delta_f\left(1-\alpha\right)$$

If $\alpha > 0$ is sufficiently small and $\rho_{d,f} > 0$, then all of the above expressions are negative, and we have a so-called "foreign auction cycle": in anticipation of the foreign auction, the yield on the domestic secondary market rises, while it decreases when the primary dealers offload their newly acquired debt. The foreign auction cycle disappears when the correlation between the two debt instruments is zero or debt markets are completely segregated, i.e. $\theta_f = 1$, and the ESCB intervenes only in the foreign secondary market. However, cross-border pay-off correlations between Eurozone sovereign debt instruments of the same maturity are generally positive (see Table 10 below), while debt market segregation can at most be partial due to the primary dealer overlaps among Eurozone countries that we described above. Assuming that the above conditions on α and $\rho_{d,f} > 0$ hold, which we will do henceforth, the negative price response of the domestic bond to a larger foreign auction is stronger when primary dealers are more risk-averse, and when the wealth they have effectively available for investment in domestic debt is smaller. A stronger ESCB response α dampens the auction cycle directly. Finally, an increase in market volatility magnifies the foreign auction cycle, while a stronger ESCB response α in turn dampens this effect.

3.4 Hypotheses

Based on our maintained assumptions that α is sufficiently small and the pay-off correlations between old and new debt in the case of a domestic auction and between domestic and new foreign debt in the case of a foreign auction are positive and sufficiently high that the expressions in Results 1 and 2 are all negative, we formulate the following hypotheses that we will investigate in our empirical analysis in Section 6:

Hypothesis 1.

a. A domestic auction produces an auction cycle in the domestic secondary market.

b. The domestic auction cycle is larger if market volatility is higher.

c. A larger intervention by the ESCB dampens the domestic auction cycle more.

d. A larger intervention by the ESCB dampens the effect of market volatility on the domestic auction cycle more.

and

Hypothesis 2.

a. A foreign auction produces an auction cycle in the domestic secondary market.

b. The foreign auction cycle is smaller in size than the domestic auction cycle, assuming that two domestic same-maturity assets are more strongly correlated than a domestic and a foreign same-maturity asset.

c. The foreign auction cycle is larger if market volatility is higher.

d. A larger intervention by the ESCB dampens the foreign auction cycle more.

e. A larger intervention by the ESCB dampens the effect of market volatility on the foreign auction cycle more.

4 Data and Construction of Variables

In the empirical analysis we use primary and secondary sovereign debt market data of Austria, Belgium, Finland, France, Germany, Italy, the Netherlands, Portugal and Spain. This set includes nine out of the eleven countries that have been member of the Eurozone from its start in 1999. The other two initial members, Ireland and Luxembourg, are not included in the analysis, because their data are incomplete. Our sample covers by far the largest part of the Eurozone in terms of GDP and population, implying that our results should be indicative for the Eurozone as a whole. For each country we investigate the 10-year sovereign debt, [15] because this generally is the most liquid and most-frequently auctioned bond. Also, the statistics presented below refer to (auctions of) 10-year debt.

The sample starts on January 1^{st}, 1999, and ends on December 29^{th}, 2017. The dataset extends that used by Beetsma et al. (2018) into the country- and time-dimension. The increased sample allows us to test our hypotheses for sub-groups of countries and for sub-periods. In particular, we are able to distinguish a period where NCBs bought sovereign debt for regular purposes, January 1^{st} 1999 - May 9^{th} 2009, and a period during which they bought sovereign debt under the APPs for unconventional monetary policy purposes, May 10^{th} 2010 - December 29^{th} 2017.

4.1 Primary Market Data

Auction data are collected from Bloomberg and cross-checked with data from the DMO's of the individual countries to obtain an accurate and virtually complete data set. In particular, of each auction we have data on the maturity, the mean accepted yield, and the total amounts bid and allotted. Only for the Netherlands mean accepted yield data are missing. Table 2 reports some summary statistics. Comparing the pre-APP and APP subsamples, we observe a substantial fall in the primary-market yields. Regarding the numbers and sizes of the auctions there is quite some variation. The mean amounts allotted range from around 600 million to 6 billion. Compared to Germany, the Spanish, French and Italian auctions occur relatively frequently, but they tend to be smaller in size, especially during the pre-APP period. Compared to the pre-APP period, the average sizes of the Spanish, Finnish, French and Portuguese auctions are proportionally substantially larger during the APP period, in line with the rise in the debt-to-GDP ratios of these countries during the crisis.

[15] That is, we investigate the effect of 10-year government bond issues on existing bonds with a remaining maturity of 10 years.

Table 2: Auction Statistics.

		Full Sample	Pre-APP	APP
AT	Number of auctions	116	49	67
	Mean amount allotted (mln €)	1235.77	1624.39	951.55
	Mean average yield (%)	2.55	4.25	1.31
BE	Number of auctions	111	52	59
	Mean amount allotted (mln €)	1222.60	1210.30	1233.44
	Mean average yield (%)	3.22	4.41	2.17
DE	Number of auctions	167	73	94
	Mean amount allotted (mln €)	4499.80	5822.38	3472.69
	Mean average yield (%)	2.49	4.13	1.22
ES	Number of auctions	180	83	97
	Mean amount allotted (mln €)	1587.62	1285.14	1846.45
	Mean average yield (%)	3.74	4.62	2.98
FI	Number of auctions	30	13	17
	Mean amount allotted (mln €)	1605.63	897.92	2146.82
	Mean average yield (%)	3.14	5.04	1.69
FR	Number of auctions	190	112	78
	Mean amount allotted (mln €)	3770.13	3237.92	4534.32
	Mean average yield (%)	3.10	4.30	1.38
IT	Number of auctions	223	129	94
	Mean amount allotted (mln €)	2762.56	2685.64	2868.12
	Mean average yield (%)	4.20	4.53	3.69
NL	Number of auctions	82	45	37
	Mean amount allotted (mln €)	2808.54	2713.64	2923.96
	Mean average yield (%)	-	-	-
PT	Number of auctions	69.00	43.00	26.00
	Mean amount allotted (mln €)	716.16	663.05	804.00
	Mean average yield (%)	4.36	4.77	3.69

Notes: AT = Austria, BE = Belgium, DE = Germany, ES = Spain, FI = Finland, FR = France, IT = Italy, NL = Netherlands, and PT = Portugal.

4.2 Secondary Market Data

4.2.1 Yields

The secondary market yields are end-of-day quotes obtained from Datastream. Table 3 reports summary statistics for the daily secondary-market yield changes in basis points. More specifically, the table reports the means and standard deviations for the full sample period, the pre-APP period and the APP period. While during the pre-APP period the average daily yield change ranges from -0.05 to 0.07 basis points, this measure falls to a range from -0.23 to -0.10 during the APP period. Going from the pre-APP to the APP period, for Italy, Spain, and Portugal, we observe a clear increase in the standard deviations of the daily yield changes, while for the other countries there is no clear pattern in this regard.

Table 3: Summary Statistics Daily Secondary Market Yield Changes.

	Full Sample	Pre-APP	APP
AT	-0.07	-0.04	-0.12
	(4.37)	(4.39)	(4.35)
BE	-0.07	-0.03	-0.14
	(4.57)	(4.20)	(5.11)
DE	-0.07	-0.05	-0.10
	(4.23)	(4.13)	(4.40)
ES	-0.05	0.00	-0.14
	(6.33)	(4.74)	(8.28)
FI	-0.07	-0.05	-0.10
	(5.05)	(5.40)	(4.43)
FR	-0.07	-0.04	-0.10
	(4.52)	(4.59)	(4.42)
IT	-0.04	-0.01	-0.10
	(5.86)	(4.31)	(7.74)
NL	-0.07	-0.01	-0.11
	(4.42)	(4.51)	(4.26)
PT	-0.05	0.07	-0.23
	(11.57)	(6.31)	(16.94)

Notes: numbers in parentheses are the standard deviations in basis points. Further, see Notes to Table 2

Table 10 in the Appendix reports the cross-border correlations between the secondary-market yield changes for the full sample period and each subperiod. Prior to the APP-period, all yield changes are positively correlated, while the correlations are substantially lower in most cases during the APP-period. In particular, the correlations of the yield changes between Germany and Italy, Germany and Spain, and Germany and Portugal fall from high to slightly negative levels. The correlation patterns during the APP-period reveal some segregation between Northern and Southern Europe.

4.2.2 Market Volatility

As our theoretical model derives the responses of sovereign bond prices to changes in market volatility rather than to changes in security-specific volatility, we use a factor model to extract a market volatility measure from the volatilities of the individual securities. More specifically, we extract the first factor of the absolute deviations from the mean of the individual countries' differenced yield series.[16] The dependent variable in our regressions are the differenced yield series, which form a close approximation to the bond returns and, hence, are inversely linked to the factors driving the bond price responses around new auctions. To ensure that our market volatility measure can be treated as exogenous in our regressions, for each country i we obtain our measure by estimating the following factor model on all countries except country i:

$$[|\Delta Y_1 - \mu_1|, |\Delta Y_2 - \mu_2|, \ldots, |\Delta Y_{i-1} - \mu_{i-1}|, |\Delta Y_{i+1} - \mu_{i+1}|, \ldots, |\Delta Y_N - \mu_N|] = f_i \Lambda_i^\top + \varepsilon$$

where $|\Delta Y_j - \mu_j|$ is a vector of length T containing the absolute deviations of the 10-year country j sovereign bond differenced yield series from its mean μ_j. Further, vector f_i, of length T, is the first factor that summarizes the individual features (being the individual volatilities) per period observation. The factor loadings vector Λ_i is of length $N-1$ and represents the change in individual volatilities due to a unit change in the factor f_i. The noise matrix ε is of size $T \times (N-1)$ and is often referred to as the individual-specific factors. From the factor model, we exclude the absolute deviation of country i's differenced yield series, in order to avoid potential simultaneity issues with our main regressions below.

We estimate the model by maximum likelihood. We are particularly interested in our market volatility measure, the estimate $\hat{f}_i$ of f_i. Figure 2 depicts $\hat{f}_i$ for every country. All measures are extremely similar, as can be expected from a general market volatility measure. Of all pairs, the lowest correlation is between the market volatility measures of France and the Netherlands, which still has a value of 0.97. In line with what is generally observed in

[16]Note that $|x - \mu| = \sqrt{(x-\mu)^2}$. Hence, absolute deviations from the mean provide a good measure of volatility.

high-frequency financial markets data, there are periods of lower and higher volatility. High volatility episodes are observed in particular in 2009 and 2012.

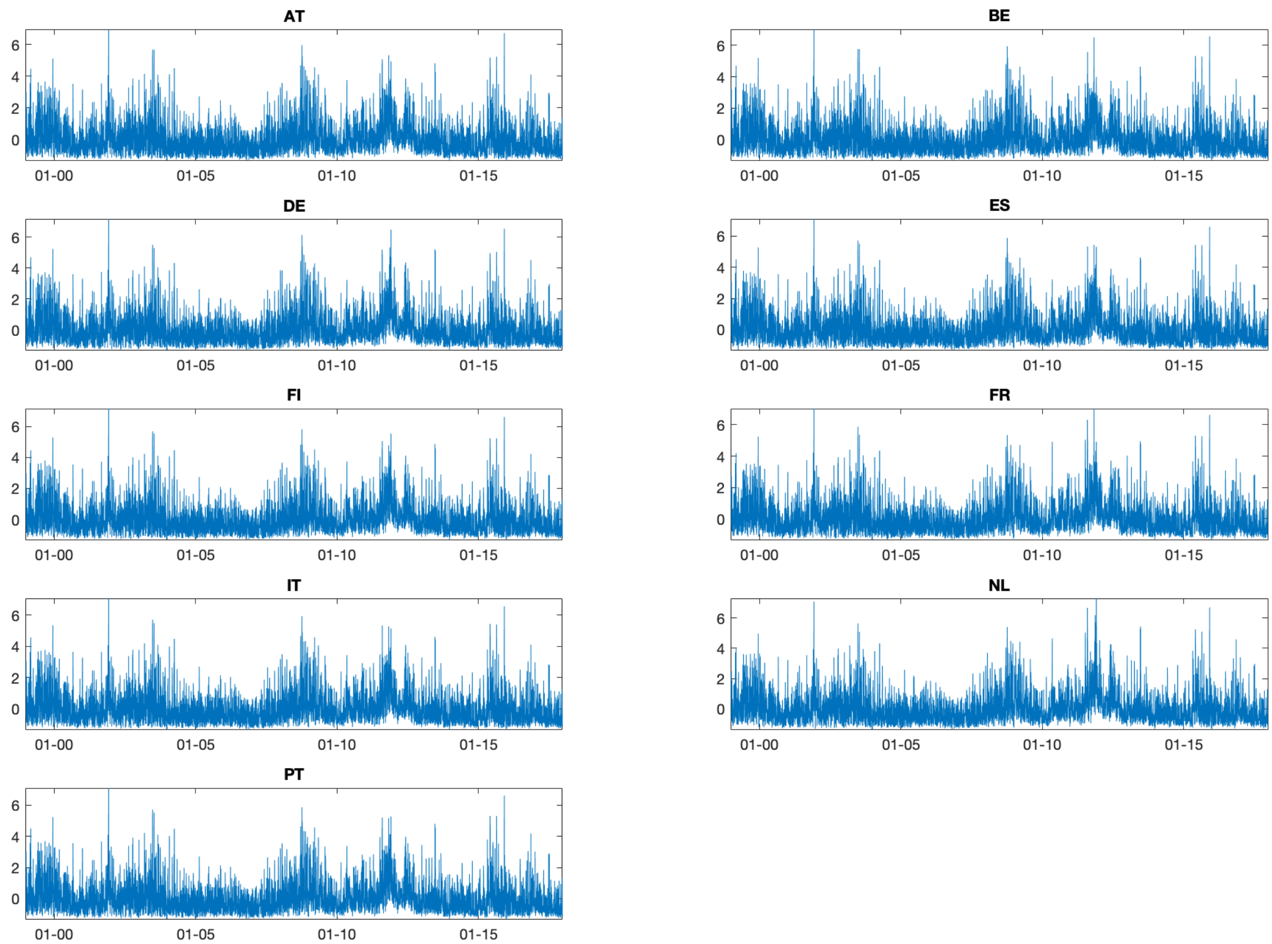

Figure 2: Market Volatility Factor.

4.3 Data Related to Sovereign Debt Purchases

The central bank asset purchases are measured by changes in the central banks' holdings of general government debt securities issued by Eurozone governments. For each country we obtain data from the ECB's Statistical Data Warehouse. The sample starts on January 4^{th} 1999 and runs until December 29^{th} 2017.

4.3.1 Net Sovereign Debt Purchases

For our analysis we are particularly interested in the ESCB's purchases of sovereign debt, as this asset category is most closely substitutable with the instruments offered in the sovereign debt auctions we study. Unfortunately, the ESCB's sovereign debt purchases are confidential information and, hence, are not directly observability. Therefore, we construct them from the sovereign debt holdings reported on the NCB balance sheets. These are reported only on a monthly basis, and are obtained from the ECB's Statistical Data Warehouse. The data include NCB and ECB end-of-month debt holdings of Eurozone general government debt.

Figure 3 depicts the NCBs' Eurozone general government debt holdings. The significant changes in the series appear with the start of the asset purchasing programs and in particular with the start of QE. However, for all countries, but Germany, the series are positive before the start of the first program, suggesting sovereign debt is also bought for purposes other than monetary policy.[17] Since we investigate changes in sovereign debt holdings the differences in starting levels when the asset purchasing programs start are not relevant. As mentioned earlier, the NCB sovereign purchases are mainly domestic debt.[18] In those cases where it is forced to deviate, it also buys European supranational debt.[19] These purchases are, however, not included in the series that we use. The ECB itself also buys sovereign debt. However, we do not add the ECB holdings to our measure of NCB sovereign debt holdings, because the issuer limit has likely been binding for the ECB at times. Hence, we would not feel comfortable apportioning the ECB holdings on the basis of the capital key to each of the NCB holdings of domestic general government debt.

[17]For instance, purchases may be made for profit to cover operating costs of the NCB.
[18]`https://www.ecb.europa.eu/explainers/tell-me-more/html/asset-purchase.en.html`
[19]`https://www.ecb.europa.eu/mopo/implement/omt/html/pspp-qa.en.html`

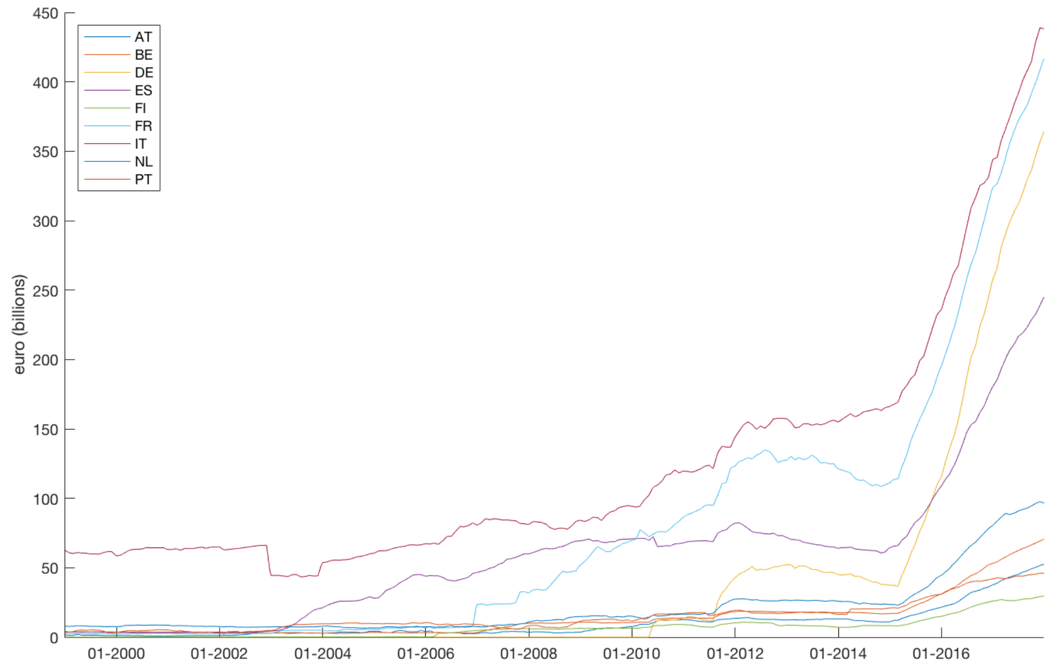

Figure 3: General Government Debt Securities Held by NCBs.

To construct series of sovereign debt purchases at the daily frequency, we evenly distribute the monthly change in the NCB debt holdings over all days in each month, excluding domestic auction and pre-auction days, hence taking into account the blackout period of the ECSB purchases.[20] In line with Article 123 of the Treaty, the prohibition on monetary financing, the ESCB tries to minimize the impact of its purchases on price formation in both the primary and secondary markets. To obtain a measure of net purchases, we set the relatively infrequent negative holdings changes, which indicate that the sum of the amounts that were redeemed and sold exceed the amount of purchases, to zero. Note that this measure includes potentially delayed purchases due to impaired market liquidity or binding issuer limits. These delayed purchases are reflected in the change in monthly holdings at a later moment. Figure 4 shows the resulting measure of net purchases. The asset purchasing programs that focus on sovereign debt are the SMP and the PSPP. Hence, major rounds of government bonds purchases took place during the periods May 2010 - September 2012 and from March 2015 until the end of our sample, which is visible in the figure.

[20]NCBs do not purchase debt securities around issuance dates. This is the so-called "blackout period". See `https://www.ecb.europa.eu/press/key/date/2017/html/ecb.sp171206.en.html`

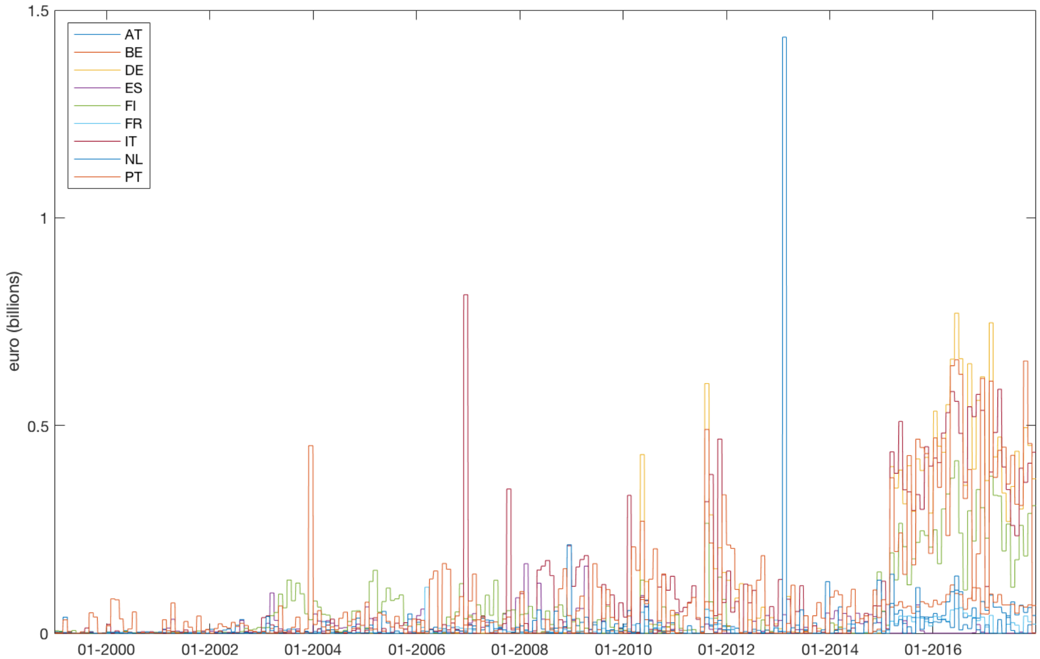

Figure 4: Net Asset Purchases

Table 4 reports the key statistics for the purchases over the full sample period, the pre-APP period and the APP period. The figures exhibit some noteworthy features. First, the average daily purchases, and their variability, drastically increased during the APP period. Further, German central bank purchases are zero during the pre-APP period – this is in line with both the ECB and the Bundesbank reporting zero general government debt holdings by the latter during this period. Finally, even though Germany has the highest capital key, daily purchases by the French central bank are largest. Purchasing volumes by the other central banks are ranked according to the capital key.

Table 4: Average Daily Purchases in Millions of Euros.

	Full Sample	Pre-APP	APP
AT	14.29	6.82	25.34
	(23.58)	(11.85)	(31.10)
BE	15.27	4.15	31.74
	(28.71)	(8.89)	(38.40)
DE	79.97	0.82	197.18
	(185.32)	(19.70)	(248.25)
ES	58.50	27.19	104.88
	(100.99)	(36.88)	(140.33)
FI	8.32	3.41	15.59
	(15.62)	(11.11)	(18.28)
FR	96.90	30.28	195.57
	(172.19)	(87.90)	(211.00)
IT	94.38	33.63	184.36
	(160.10)	(61.05)	(204.24)
NL	23.53	7.19	47.72
	(43.37)	(12.93)	(58.64)
PT	14.35	10.36	20.25
	(22.75)	(16.78)	(28.44)

Note: numbers in parentheses are the standard deviations in millions of euros. Further, see Notes to Table 2.

4.3.2 Market Depth

Since the ESCB reinvests redemptions, its stock of asset holdings grows steadily over the QE period. This affects the depth of secondary sovereign bond markets, which may in turn affect the servicing cost of new sovereign debt. We define "market depth" as the difference between the level of outstanding euro denominated sovereign debt with residual maturity over one year minus the sovereign debt holdings of NCBs. The implicit assumption is that the NCBs only hold debt issued by their own country, in line with the policy of excluding risk sharing among Eurozone member states. Market depth measures the component of the outstanding debt stock that is effectively tradable in secondary markets. Again, we obtain the data on outstanding sovereign debt from the ECB's Statistical Data Warehouse and linearly interpolate these (quarterly) data to obtain a series at the daily frequency. Figure 5 depicts our market depth measure. Clearly, market depth has been deviating more and more from the outstanding stock of sovereign debt since the start of the PSPP.

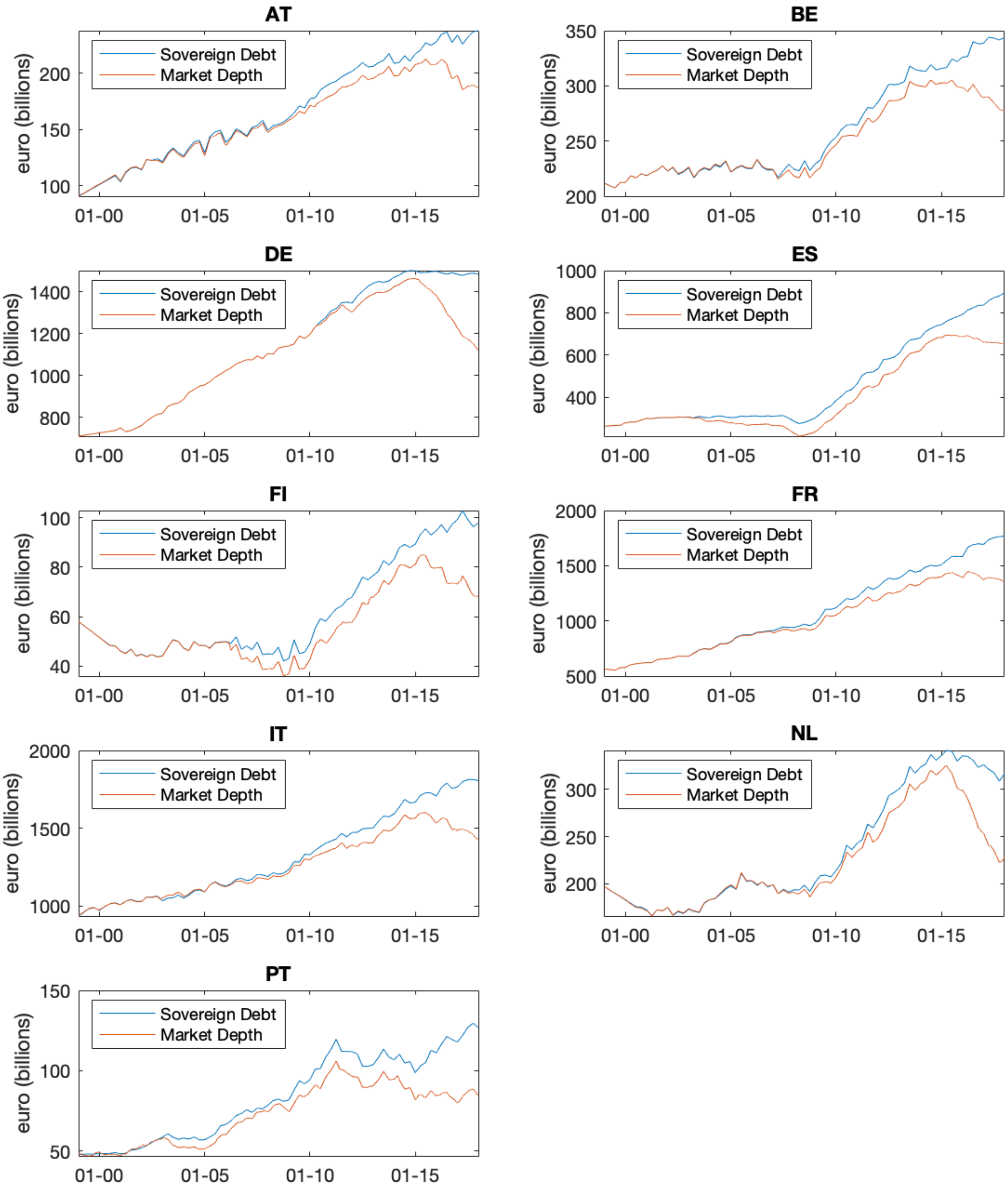

Figure 5: Market Depth

4.4 Credit ratings

We gather credit ratings from Fitch,[21] and create two country clusters based on these ratings for future use. Countries with a rating of AA+ or higher are assigned to Cluster 1, while the other countries are assigned to Cluster 2. The two clusters are listed in Table 5.

Table 5: Country Clusters

Cluster 1	AT	DE	FI	NL	
Cluster 2	BE	ES	FR	IT	PT

Note: see notes to Table 2.

5 Event study

As a stepping stone towards the ensuing regression analysis, this section presents an event study of the behaviour of secondary market yields around auction dates. Similar event studies are conducted by Lou et al. (2013), who provide evidence for the United States of an inverse V-shaped pattern of secondary market yields around auction dates, and Beetsma et al. (2016, 2018), who present similar evidence for Eurozone countries. Our event window spans the period of the four trading days before the auction day, the auction day, and the five days after an auction. Figure 6 reports the average, calculated over the full sample period, of the secondary market yield difference $y_t - y_0$ between the end of day t and the end of the auction day, which is indicated by subscript 0. The figure also depicts the 10% confidence bounds. In line with the existing literature, we tend to observe an increase in the secondary market yield prior to the auction and a decrease after the auction. This decrease suggests that a larger supply resulting from auctions can not be the sole instigator of auction cycles. The cycle pattern tends to be more pronounced for the countries with a relatively low credit rating. The highest-rated countries, such as Germany and the Netherlands do not exhibit much of a cycle, possibly because any debt they issue is almost guaranteed to be absorbed by institutional investors and other traders. The auction cycle pattern is particularly strong when all observations are pooled. The "average" auction cycle also appears to be roughly

[21]Source: `https://tradingeconomics.com/country-list/rating?continent=europe` on January 16, 2019.

symmetric. Obviously, this event study neglects the potential role of confounding factors, such as debt auctions in other Eurozone countries. Hence, the results of this section motivate the more fully-fledged empirical analysis in the next section.

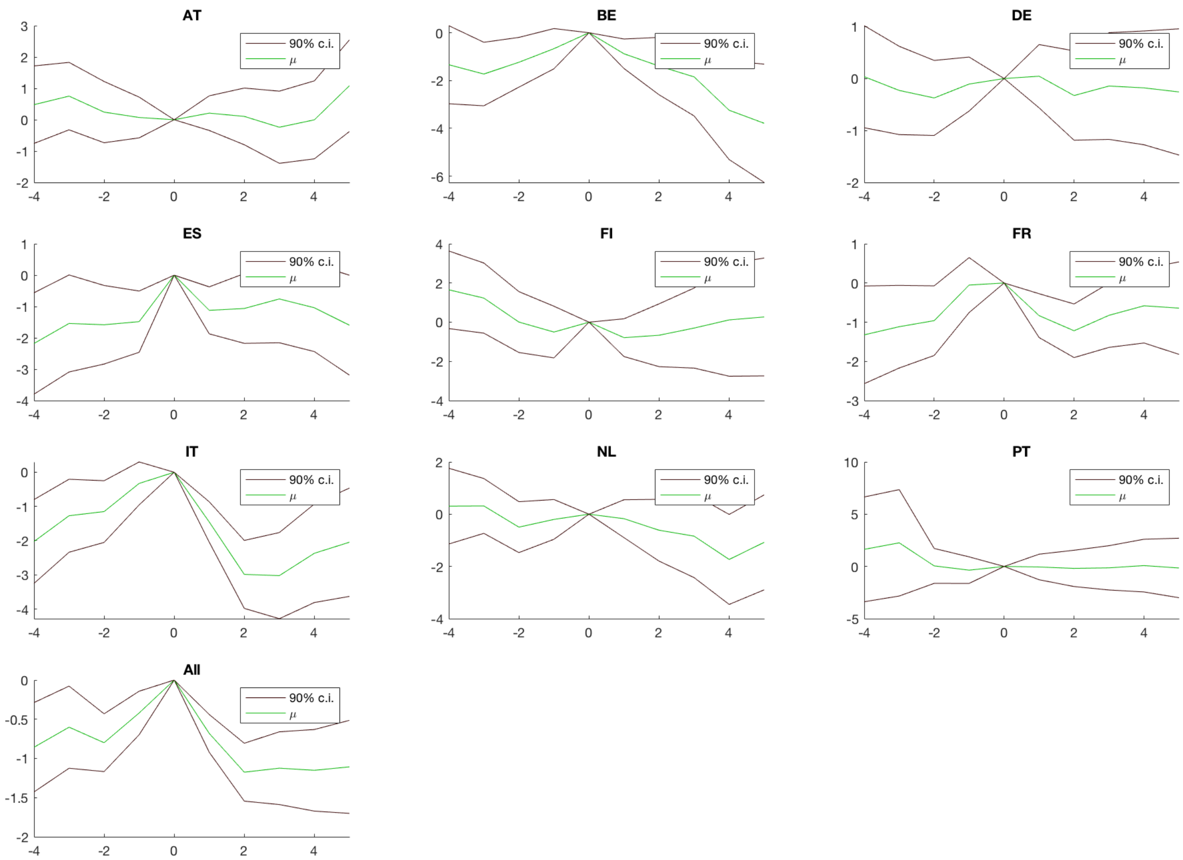

Figure 6: Event Study.

6 Results from Panel Regressions

This section uses panel regressions to empirically investigate the hypotheses put forward by our theoretical framework. While recent research already showed the existence of auction cycles (Lou et al. 2013, Beetsma et al. 2016, 2018), we extend this work into a variety of directions, in particular by allowing for a role of ESCB interventions.[22] As all auction

[22]We refrain from including other unconventional monetary policy instruments in our analysis, such as the targeted long-term refinancing operations (TLTROs). They may indeed raise the demand for newly-issued debt, which could be used as collateral for the TLTROs. In view of our theory, we would expect this to dampen the auction cycle. However, we do not have sufficiently granular data to test this effect. We would

dates for the coming year are known in advance, the occurrence of an auction is exogenous. We start by regressing secondary-market yield changes on dummies for the occurrence of domestic and foreign auctions and the interaction of these dummies with our market volatility measure, changes in central bank sovereign debt holdings and the interaction of the latter two variables.[23] Not only do we contribute to the existing literature by controlling for sovereign debt purchases, but also by investigating the roles of general market uncertainty and market depth. Moreover, the larger dataset compared to the existing literature in both the time and the cross-sectional dimension allows us to conduct our estimations not only on the full sample, but also on the APP sub-sample and on the country clusters formed on the basis of their credit ratings. Supported by the cross-country differences found in the event study, we estimate cluster-specific responses to domestic auctions and allow for differences in spill-overs from foreign auctions in the own and the other cluster.

6.1 Panel Regressions on the Full Country Sample

6.1.1 Baseline Regression

Although the sample stretches over a long period in time, public debt auctions occur relatively infrequently. The number of auctions for a given country can therefore be relatively small. Hence, we deploy a fixed-effects panel regression model, imposing that the auction cycles are identical across the sample countries. In contrast to a random effects model, this specification allows for a non-zero correlation in the general level of the yield changes and the covariates.

need information on the amount and maturity of the collateral underlying the TLTROs, while only the volume of the credit provided under the TLTROs is public information.

[23]We do not explore the direct effect of the auction size on the auction cycle, because the amount that is allotted may respond to yield changes during the run-up to the auction. The alternative would be to use the targeted issuance amounts that are communicated prior to the auctions. However, we only have these data for a subset of countries. Hence, our regressions are based on auction date dummies.

The baseline regression specification is:

$$
\begin{aligned}
\Delta y_{i,t} = a_i + &\sum_{l=4}^{-5} AUC_{i,t+l}(\alpha_l + \beta_l VOL_{i,t} + \gamma_l \Delta DH_{i,t} + \delta_l VOL_{i,t}\ \Delta DH_{i,t}) \\
&+ \sum_{l=4}^{-5} \sum_{j \neq i} AUC_{j,t+l}(\zeta_l + \theta_l VOL_{j,t} + \kappa_l \Delta DH_{j,t} + \lambda_l VOL_{j,t}\ \Delta DH_{j,t}) \\
&+ \mu' VOL_{:,t} + \nu' \Delta DH_{:,t} + \pi' \left[VOL_{1,t}\Delta DH_{1,t}, \ldots, VOL_{N,t}\Delta DH_{N,t}\right]' \\
&+ \tau' \Delta X_{t-1} + \varepsilon_{i,t} \qquad [1]
\end{aligned}
$$

where:

- $\Delta y_{i,t}$ is the change in basis points in the secondary market yield of the sovereign bond of country i at time t.

- a_i is a country-specific intercept.

- $AUC_{i,t}$ is a dummy variable which equals one when there is a sovereign debt issue by country i at time t, and zero otherwise.

- $VOL_{i,t}$ is the market volatility measure constructed in Subsection 4.2.2. Note that we only interact the current volatility with the auction dummies. It is well known that to obtain the marginal effects one needs to include all the variables included in the interaction terms also individually in the regression. Hence, by interacting all the auction dummies of a specific country with the current value of the volatility variable, we only need to control for this current value.[24] The vector $VOL_{:,t}$ contains $VOL_{i,t}, \forall i \in \{1, 2, \ldots, 9\}$.

- $\Delta DH_{i,t}$ is the change in billions of euros of country i's central bank holdings of general government debt securities issued by Eurozone governments at time t. As explained in Subsection 4.3, the change in central bank sovereign debt securities holdings is

[24] This limits the number of parameters to be estimated compared to the case in which we would interact the $t+l$ auction dummy with $VOL_{i,t+l}$, which would a priori be seen as a natural specification. Incidentally, replacing $VOL_{i,t}$ by $VOL_{i,t+l}$ in our specification yields very similar results, which is not surprising due to the clustering characteristic of volatility. However, under this specification we would need to include individually all of the ten $VOL_{i,t+l}$ interacted with the domestic auction dummies. Similarly, for the $VOL_{j,t+l}$.

constructed by allocating changes in holdings evenly over the month, taking into account the blackout period. We only include the current (period-t) change in debt holdings. The elements of the vector $\Delta DH_{:,t}$ are $\Delta DH_{i,t}, \forall i \in \{1, 2, \ldots, 9\}$.

- X_t is a vector of covariates capturing European financial market conditions. By controlling for these covariates we eliminate the possibility that our auction cycle estimates are driven by (fluctuations in) current market conditions. Our covariates include the Euro Overnight Index Average (EONIA),[25] the Euro Stoxx 50 Index, the Euro Stoxx Banks Index, and the Euro Stoxx 50 Volatility Index (VSTOXX).[26] Hence, we control, respectively, for conditions in the interbank lending market, the European equity market and the European banking sector, as well as the option-implied volatility in European equities. To prevent any feedback effects from sovereign debt yield changes to the conditions in European financial markets, we include the first lag of the change in the EONIA rate and the first lag of the log change in the other indices.

The first summation in regression [1] includes the last four days before each auction ($0 < l \leq 4$), the day of the auction ($l = 0$), and first 5 days after the auction ($-5 \leq l < 0$), implying ten domestic auction dummies. The second summation is similar, but sums over the auction dummies for all countries other than i. To limit the number of parameters to be estimated, for now we impose identical cross-border effects from all auctioning foreign countries. Later we relax this assumption and group countries into clusters.

An auction cycle is characterized by an increase in the secondary market yield during the run-up to the auction and a decrease in the yield after the auction. Hence, using F-tests,[27] we test the null hypotheses of the absence of a domestic, respectively foreign, auction cycle:

$$H_0 : AC \equiv \sum_{l=4}^{0} \alpha_l - \sum_{l=1}^{-5} \alpha_l = 0, \;\; H_0 : ACF \equiv \sum_{l=4}^{0} \zeta_l - \sum_{l=1}^{-5} \zeta_l = 0$$

[25]The data is available at the ECB's SDW: https://sdw.ecb.europa.eu/quickview.do?SERIES_KEY=198.EON.D.EONIA_TO.RATE.

[26]Data is available at the STOXX digital website: https://www.stoxx.com.

[27]We use the F-test proposed by Hansen (2007), which is valid for fixed effects models when the number of individuals is small and the time dimension is large. This test is based on the heteroskedasticity and autocorrelation consistent covariance matrix proposed by Arellano (1987).

To study the effect of market volatility on auction cycles, we deploy a similar test:

$$H_0 : AC \times VOL \equiv \sum_{l=4}^{0} \beta_l - \sum_{l=1}^{-5} \beta_l = 0, \qquad H_0 : ACF \times VOL \equiv \sum_{l=4}^{0} \theta_l - \sum_{l=1}^{-5} \theta_l = 0$$

We allow for a possible direct negative effect of a change in central bank debt holdings on the yield increase around auctions and for a possible dampening through central bank purchases of the effect of market volatility on the yield change. Hence, we use F-tests for the following hypotheses:

$$H_0 : AC \times \Delta DH \equiv \sum_{l=4}^{0} \gamma_l - \sum_{l=1}^{-5} \gamma_l = 0, \qquad H_0 : ACF \times \Delta DH \equiv \sum_{l=4}^{0} \kappa_l - \sum_{l=1}^{-5} \kappa_l = 0$$

$$H_0 : AC \times VOL \times \Delta DH \equiv \sum_{l=4}^{0} \delta_l - \sum_{l=1}^{-5} \delta_l = 0, \quad H_0 : ACF \times VOL \times \Delta DH \equiv \sum_{l=4}^{0} \lambda_l - \sum_{l=1}^{-5} \lambda_l = 0$$

Column [1] of Table 6 reports the panel estimates of AC and ACF, the Born-Breitung (2016) statistic BB for serial correlation, which is robust against heteroskedasticity in the time dimension,[28] and the adjusted R-squared R^2_{adj}. In line with the empirical asset pricing literature, the adjusted R-squared is low. The Born-Breitung (2016) statistic is insignificant. Although this statistic suggests that a static, instead of a dynamic, panel data model may suffice, in order to be conservative we use a robust covariance matrix to base our inferences on.

Consistent with the theoretical model, and confirming the results of Beetsma et al. (2018), the highly-significant estimates of AC provide evidence for the existence of both domestic and foreign auction cycles. Further, the foreign auction cycle estimate captured by ACF is smaller than its domestic counterpart. Based on the theoretical framework, this is what one would expect if the correlation of the existing domestic benchmark asset with the auctioned domestic asset exceeds that with the auctioned foreign asset. Moreover, the estimates show that an increase in market volatility magnifies both the domestic and foreign auction cycle. Hence, our estimates support Hypotheses 1a, 1b and 2a - 2c derived in Subsection 3.4.

[28] Whereas the standard Bhargava (1982) statistic, which is the Durbin-Watson statistic adapted for panel data models, loses validity when heteroskedasticity in the time dimension is present, the statistic proposed by Born & Breitung (2016) is robust against this form of heteroskedasticity.

In line with Hypotheses 1c and 2d, there is strong evidence of a direct dampening effect of central bank sovereign debt purchases on both domestic and foreign auction cycles. A billion euros worth of sovereign debt purchases suppresses the cycle associated with domestic auctions by 6.8 basis points and the cycle associated with foreign auctions by 4.2 basis points. The contribution of the interaction of the auction dummies with market volatility is dampened by the sovereign debt purchases, although the effect is only significant for the foreign auction cycle. Hence, the results are suggestive of the relevance of Hypothesis 1d, and quite supportive of Hypothesis 2e. None of the controls for the state of European financial markets are significant.

Beetsma et al. (2018) also provide empirical evidence for symmetry in secondary-market yield movements around auctions, i.e. whether the pre-auction increase in the yield equals the post-auction fall in the yield.[29] We test the symmetry assumption for the domestic and the foreign auction cycle. The test reported in Column [1] of Table 6 does not reject symmetry in the domestic auction cycle, suggesting that the proposed F-tests are appropriate for testing the presence of auction cycles. Although symmetry in the foreign auction cycle is rejected, in our ensuing regressions symmetry can not always be rejected. Hence, we continue to economize on the numbers of parameters by not specifying different trajectories for the secondary-market yields before and after the auctions.

In line with the discussion in Beetsma et al. (2018) we can dismiss potential alternative explanations of the observed auction cycles. First, a new issue could increase the total supply of the outstanding debt if it is not used to replace maturing debt. Hence, a supply effect cannot a priori be excluded – after all, a number of sample countries have seen their total public debt-GDP-ratios increase during the Eurozone debt crisis; recall Figure 5. However, if increased supply is the sole driver of the yield increases prior to the auction, then we would not expect yields to come down after the auction. Since we do see yields return to roughly their original levels, as was also evident from our event study, this suggests that the

[29] For example, for the domestic auction cycle, this would amount to testing whether $AC_1 \equiv \sum_{l=4}^{0} \alpha_l$ and $AC_2 \equiv \sum_{l=1}^{-5} \alpha_l$ are equal in absolute value.

supply effect hypothesis is not the driving force behind the auction cycles. An alternative hypothesis is that yields increase because the current on-the-run benchmark instrument goes off the run after the auction. Hence, it becomes less attractive for repo transactions (e.g., see Sundaresan 1994), which suppresses its price. However, this hypothesis sits uneasily with the fact that most auctions are reopenings of existing instruments and that the price of the auctioned instrument rises after the auction, while the on-the-run premium is highest immediately after the auction and falls thereafter (see Krishnamurthy, 2002).

Table 6: Testing For Auction Cycles.

	[1]	[2]	[3]	[4]	[5]	[6]	[7]
AC	2.70**	3.83*	4.80	2.95***	3.46	2.87***	3.35
$\times VOL$	2.11	4.46*	4.67*	3.41***	4.27*	3.12***	3.83*
$\times \Delta DH$	−6.80***	−8.98**	−6.54	−8.16**	−5.73	−3.12*	−1.67
$\times \Delta DH \times VOL$	−1.53	−2.83	−3.53	−12.59	−1.11	−4.19	0.44
$\times MktDepth$			−1.55				
ACF	1.31***	1.23	1.50**	1.39***	1.45*	1.46***	1.45*
$\times VOL$	1.88***	3.17***	3.32***	2.19***	4.08***	2.08***	3.67***
$\times \Delta DH$	−4.16***	−3.82***	−4.51***	−3.63***	−4.99***	−1.91***	−1.66***
$\times \Delta DH \times VOL$	−4.31***	−4.98***	−5.60***	−5.66**	−9.73***	−2.19***	−2.48***
$\times MktDepth$			1.00*				
Δ Eonia	0.16	−0.27	0.28	0.18*	−0.11	0.15	−0.25
Δ Eurostoxx50	−0.01	−0.28***	−0.27***	−0.02	−0.29***	−0.01	−0.28***
Δ Eurostoxx Bank	−0.13	−0.07	−0.08	−0.12	−0.05	−0.13	−0.06
Δ VSTOXX	0.00	−0.01	−0.01	0.01	−0.01	0.01	−0.01
BB	1.45	2.04**	2.03**	1.42	2.01**	1.47	2.06**
R^2_{adj}	0.04	0.05	0.05	0.05	0.05	0.04	0.05
T	4853	1949	1949	4853	1949	4853	1949
N	9	9	9	9	9	9	9
Symmetry AC	0.82	1.68*	1.81	1.13	1.32	1.02	1.50*
Symmetry ACF	0.60***	1.08*	2.89***	0.60*	0.66	0.51*	0.79

Notes: (i) One, two and three asterisks indicate the 10, 5 and 1% significance levels, respectively. (ii) Column [1] reports the estimates of the baseline regression equation, Column [2] the estimates on the APP subsample, and Column [3] the estimates for the APP subsample including market depth effects, Columns [4] and [5] repeat repeat Columns [1] and [2] when home and foreign purchases are scaled by outstanding sovereign debt of the respective countries, Column [6] and [7] idem with GDP as the scaling factor.

6.1.2 The APP Sub-Sample

The start of the APPs of the ESCB may have constituted a change in the policy regime. While in the preceding period central banks may occasionally have purchased sovereign bonds for various possible reasons, the purchases of Eurozone sovereign debt under the APPs were specifically intended to improve the functioning of the monetary transmission mechanism. In this subsection, we re-estimate [1] for the subperiod starting on May 10^{th} 2010, the start of the SMP program. The estimates are found in Column [2] of Table 6. Compared to the full sample estimates in Column [1], the point estimates of the direct effects of domestic and foreign auctions remain of roughly the same magnitude, but decrease in significance. The effect of the interaction between the auction dummies and market volatility becomes larger and significant in the case of the domestic auction dummies. The direct negative effect of changes in central bank sovereign debt holdings and the indirect effect through the interaction with market volatility increase for the domestic auction cycles, while both effects remain of roughly their original size for the foreign auctions.

6.1.3 Controlling for Market Depth

Conversation with senior central bank officials suggests that they are grappling with the question whether it is the stock or the flow effect of the ESCB's asset purchases that is most important in reaching its goals. So far, we have controlled for the flow effect of the asset purchases. By including market depth we control for the size of the market, i.e. the stock effect. A priori we would expect that an increase in market depth would reduce the effect of auctions on yield changes, because the size of a given auction relative to the volume available for trade in the secondary market is smaller. Column [4] of Table 6 reports the estimates of the baseline regression specification when we add the interactions of the domestic and foreign auction dummies with the domestic, respectively foreign market depth variables in trillions of euros (indicated by "$MktDepth$"). The domestic interaction features a negative and insignificant coefficient, while the foreign interaction features a positive and weakly significant coefficient, suggesting that there is no obvious effect of market depth on the size of the auction cycles.

6.1.4 Scaling Net Purchases

To control for the size of an individual country's economy, we present the results for regression [1], in which we scale the net purchases $\Delta DH_{i,t}$ by country i's outstanding debt or GDP.[30] Similarly, in the regression we scale foreign purchases $\Delta DH_{j,t}$ by country j's outstanding debt or GDP. The idea is that a given purchase of sovereign debt has a smaller effect on secondary market yields when this market is larger. To avoid problems of multicollinearity, we no longer control for market depth in the regressions. Columns [4] and [5] of Table 6 are based on scaling purchases by outstanding debt, while Columns [6] and [7] are based on scaling them by GDP. Columns [4] and [6] report the estimates for the full sample, while Columns [5] and [7] display the results for the APP subsample. Apart from the differences in the point estimates due to the different sizes of the purchases variables, the results remain qualitatively very robust. A difference with the unscaled regressions is that direct dampening effect of the sovereign debt purchases on the domestic auction cycle weakens during the APP period.

6.2 Cluster Regressions on the APP Sample

In this subsection, we relax the assumption that the effects of auctions are homogeneous over all countries. We consider the division of countries into the two clusters of high-rated countries (Cluster 1) and low-rated countries (Cluster 2) in Table 5. Beetsma et al. (2016) find substantially stronger evidence of auction cycles for Italy than for Germany. The experience of the Eurozone debt crisis suggests that anxiety about the placement of new debt is generally higher for countries in a more precarious budgetary situation than for countries with a more solid budgetary position.[31][32] Hence, it cannot a priori be excluded

[30]That is, we replace $\Delta DH_{i,t}$ by $(\Delta DH_{i,t})/Y_{i,t}$ or $(\Delta DH_{i,t})/D_{i,t}$, where $Y_{i,t}$ is country i's GDP and $D_{i,t}$ is country i's debt. We obtain outstanding debt (of maturity over one year) and quarterly GDP data from the ECB's Statistical Data Warehouse (SDW).

[31]For example, in the fall of 2018, market nervousness about an Italian auction led the Financial Times (October 11, 2018) to write "Italy's cost of funds has hit a five-year high in its latest debt auction, as the wider market sell-off and investors' jitters over its domestic politics continue to push bond yields up. [...] The bond sale was pushing the limits of investors' appetite for Italian debt – it had a bid-to-cover ratio of 1.26 per cent."

[32]For an overview of the Eurozone sovereign debt crisis and the strategies of the peripheral countries to regain market access, see Strauch et al., 2016.

that secondary markets react differently around the auction dates of these different groups.

Moreover, it is conceivable that the sovereign debt yields respond differently to auctions of countries in the same cluster than in the other cluster. For example, the substitutability in investment portfolios between a domestic bond and a foreign bond from the same cluster could be higher than between a domestic bond and a foreign bond from the other cluster.[33] Another reason could be the possibility of contagion taking the form of difficulties in placing debt spilling over from one country to another country in the same cluster. Hence, we differentiate between the foreign auction effects from countries in the same cluster and from countries in the other cluster:

$$\begin{aligned}\Delta y_{i,t} = a_i + &\sum_{l=4}^{-5} AUC_{i,t+l}(\alpha_{c_i,l} + \beta_{c_i,l}VOL_{i,t} + \gamma_{c_i,l}\Delta DH_{i,t} + \delta_{c_i,l}VOL_{i,t}\Delta DH_{i,t}) \\ &+ \sum_{l=4}^{-5}\sum_{k=1}^{2}\sum_{j\in C_k\setminus\{i\}} AUC_{j,t+l}(\zeta_{c_i,c_k,l} + \theta_{c_i,c_k,l}VOL_{j,t} + \kappa_{c_i,c_k,l}\Delta DH_{j,t} \\ &+ \lambda_{c_i,c_k,l}VOL_{j,t}\Delta DH_{j,t}) \\ &+ \mu VOL_{:,t} + \nu'\Delta DH_{:,t} + \pi'\left[VOL_{1,t}\Delta DH_{1,t},\ldots,VOL_{N,t}\Delta DH_{N,t}\right] \\ &+ \tau'\Delta X_{t-1} + \varepsilon_{i,t}\end{aligned} \qquad [5]$$

where groups C_1 and C_2 refer to clusters one and two, respectively. The parameter $\zeta_{c_i,c_k,l}$ should be read as the lag l effect from an auction by a country in cluster C_k on a country in the cluster C_i, which contains country i. Note that if country i does not belong to C_1, then $C_1 \setminus \{i\} = C_1$, and likewise for C_2. This regression specification allows for spill-overs from foreign countries in the same cluster as country i, in which case $k = i$, and from foreign countries in the other cluster.

[33] However, there is no obvious evidence to support this. Based on the correlations in Table 10 in the Appendix (not for publication) we find that the average correlations between countries in clusters 1 and 2 are 0.73 and 0.53, respectively, while the average correlation between countries across the clusters is 0.48. In fact, based on Table 10, one could potentially identify three separate clusters. Belgium and France are somewhat different than their peers in cluster 2, which suppresses the average intra-cluster correlation in cluster 2. However, as auctions occur rather infrequently, the amount of data would be too limited to estimate three different cluster-specific parameter sets. Moreover, based on Table 10 the division into the three clusters would merely be based on the data instead of an economic interpretation.

The estimates are reported in Column [1] of Table 7. Column [2] and [3] report the estimates based on scaling with the stock of outstanding debt and GDP, respectively. Again, the estimates are highly consistent across the specifications. The direct effects of the domestic auction dummies and their interaction with market volatility are smaller than before for the high-rated countries, while for the low-rated countries they are substantially larger and more significant (for example, compare Column [1] of Table 7 with Column [3] of Table 6), thereby indicating that during the period since the start of the European debt crisis, the secondary markets of low-rated countries behaved markedly differently from those of the high-rated countries. A potential explanation lies in the higher pay-off uncertainty for lower-rated countries: the expressions in Result 1 show that the negative price effect of a domestic auction as well as the sensitivity of this response to an increase in market volatility are larger when the country-specific volatility component is larger.[34] The interaction of central bank asset purchases with domestic auction dummies exerts a negative effect on the size of the auction cycle, although this effect is only mildly significant for the low-rated cluster. The three-way interaction of the domestic auction dummies with volatility and central bank asset purchases is highly significant for the high-rated cluster. As expected, the interaction of the domestic auction dummies with market depth is negative, although it is significant only for the high-rated cluster. This suggests that, during the APP period, besides flow effects, stock effects of the central bank asset purchases have had some effect on the auction cycles.

The regression without the scaling of debt purchases in Column [1] shows that cross-border effects from countries in the high-rated cluster onto other countries in both clusters are absent, except for a significant negative direct easing effect of sovereign debt purchases onto other high-rated countries and a positive effect of market depth onto the auction cycle of the low-rated countries. We do not have an obvious economic explanation for the latter effect. A potential reason could be that more market depth in high-rated bonds makes those bonds relatively more attractive, because the liquidity in this market is higher. The cross-border effects of foreign auctions in the low-rated cluster onto the other countries in

[34]Under our maintained assumption that α is sufficiently small and assuming that $\delta_{d,n} = \delta_{d,o}$, which is the case for re-openings (the majority of the auctions), both expressions in Result 1 are decreasing in $\delta_{d,n}$.

both clusters are highly significantly positive for the auction dummies and their interaction with volatility, and highly significantly negative for the auction dummies interacted with the central bank purchases and the three-way interaction of the auction dummies with volatility and central bank purchases in the case of high-rated countries. The interaction of the auction dummies with market depth is highly significantly negative for the spill-overs onto the high-rated cluster and insignificant for the spill-overs onto the low-rated cluster. Overall, the cross-border spill-over effects from auctions by low-rated countries quite well in line with our theory. The estimates when debt purchases are scaled by outstanding debt or GDP are quite well in line with the those when scaling is absent. The three-way interaction effects of domestic auction dummies, debt purchases and volatility cease to be significant for the high-rated domestic auction cycle, while the interaction of the domestic auction dummies with debt purchases ceases to be significant for the low-rated domestic auction cycle. By contrast, debt purchases of high-rated countries exert a highly-significantly negative effect on auction cycles of other high-rated countries both directly and when interacted with volatility. Auctions by foreign low-rated countries exert highly-significant positive effects on other countries from both clusters when they are interacted with volatility and highly-significant negative effects when they are interacted with the scaled debt purchases. The three-way interaction with volatility only exerts a highly-significant negative spill-over from low-rated onto the high-rated countries.

Comparing the results with those for the full sample period, Table 6 suggests that domestic auction cycles have in general become stronger and more responsive to market volatility for low-rated countries. Potential, and non-exclusive, explanations are the increase in the size of the auctions of these countries since the start of the debt crisis (see Table 2) and the shrinkage of trading capital of major primary dealers (see Beetsma et al., 2018), which may have contributed to increased market risk aversion.

Table 7: Cluster-Specific Effects for the APP period.

	[1]		[2]		[3]	
	C_1	C_2	C_1	C_2	C_1	C_2
AC	-0.13	8.16^{***}	-1.21	6.72^{***}	-1.34	7.20^{***}
$\times VOL$	-0.44	8.69^{***}	-0.18	6.84^{***}	-0.57	7.39^{***}
$\times \Delta DH$	-4.10^{***}	-10.46^{*}	-4.50^{**}	-6.73	-1.79^{**}	-3.44
$\times \Delta DH \times VOL$	-7.49^{***}	-3.67	-4.28	3.86	-1.48	0.18
$\times MktDepth$	-2.30^{***}	-1.11				
ACF_{C_1}	-0.19	-1.04	0.17	0.82^{*}	-0.02	0.84
$\times VOL$	0.36	0.30	1.46^{*}	0.29	0.91	0.17
$\times \Delta DH$	-2.53^{*}	-2.03	-5.86^{***}	2.16	-2.07^{***}	1.08
$\times \Delta DH \times VOL$	-2.87	2.67	-7.84^{***}	1.02	-2.47^{***}	0.40
$\times MktDepth$	-0.54	3.46^{**}				
ACF_{C_2}	2.27^{***}	2.83^{***}	0.44	3.74^{*}	0.56	3.89^{**}
$\times VOL$	4.07^{***}	6.27^{***}	4.21^{***}	6.11^{***}	4.25^{***}	6.44^{***}
$\times \Delta DH$	-2.42^{**}	-6.36^{***}	-4.95^{***}	-10.53^{***}	-2.03^{***}	-3.84^{***}
$\times \Delta DH \times VOL$	-8.74^{***}	-4.29	-10.23^{***}	-0.37	-3.45^{***}	-0.39
$\times MktDepth$	-2.84^{***}	0.41				
Δ Eonia	0.66		0.23		0.03	
Δ Eurostoxx50	-0.22^{***}		-0.28^{***}		-0.27^{***}	
Δ Eurostoxx Bank	-0.01		-0.07		-0.09	
Δ VIX	-0.01		-0.01		-0.01	
BB	1.90^{*}		1.97^{**}		1.99^{**}	
R^2_{adj}	0.07		0.06		0.06	
T	1949		1949		1949	
N	9		9		9	

Notes: (i) one, two, and three asterisks indicate the 10, 5 and 1% significance levels, respectively. (ii) ACF_{C_i} is the effect of foreign auctions of countries in cluster i, C_i. (iii) Column [1] reports the cluster estimates, Columns [2] and [3] the estimates based on the debt and GDP scaling factor, respectively.

6.2.1 Potential Endogeneity

Although ESCB asset purchases can only differ from their monthly budget under rather specific conditions, including among the explanatory variables current-period changes in central bank sovereign debt holdings could raise questions about potential endogeneity. First, if there exists a feedback from yield changes to changes in central bank sovereign debt holdings, the exogeneity of the explanatory variables involving asset purchases would be violated. An example would be when central banks respond to rising yields during the auction run-up by buying more sovereign debt. However, such a feedback effect would be unlikely, because it would violate the premise on which the ESCB asset purchases are based, which is that they are conducted while trying to keep their influence on financial markets to a minimum. Second, by interpolating the monthly changes in debt holdings we may by construction use information pertaining to the rest of the month. While endogeneity is unlikely in view of the various restrictions that the ESCB has imposed upon itself, we still want to explore the robustness of the results with an instrumental variables (IV) regression. As there are, on average, 22 workings days in a month, we instrument our linearly-interpolated change in the debt holdings measure by its 22^{nd} lag. This is a suitable instrument as it is highly correlated with the potentially endogenous covariate and most likely exogeneous. The results are obtained by two-stage least squares (2SLS). Concretely, we estimate the following first-stage regression:

$$\begin{aligned}\Delta DH_{i,t} = b_i + \phi_i \Delta DH_{i,t-22} + \sum_{l=4}^{-5} AUC_{i,t+l}(\Upsilon_{1,l} + \Upsilon_{2,l} VOL_{i,t}) \\ + \sum_{l=4}^{-5} \sum_{j \neq i} AUC_{j,t+l}(\Phi_{1,l} + \Phi_{2,l} VOL_{j,t}) \\ + \Psi_1 VOL_{:,t} + \Psi_2 \Delta DH_{:,t} + \Psi_3 \left[VOL_{1,t}\Delta DH_{1,t}, \ldots, VOL_{N,t}\Delta DH_{N,t}\right]' \\ + \eta_{i,t}\end{aligned} \quad [6]$$

The second stage consists of regression equation [5] with $\Delta DH_{i,t}$ and $\Delta DH_{j,t}$ replaced by the fitted values $\widehat{\Delta DH}_{i,t}$ and $\widehat{\Delta DH}_{j,t}$ from the first-stage regression. The estimates are reported in Table 11 in the Appendix. The estimates are in general similar in size and significance to those in Table 7.

6.3 Budgetary Significance of the Estimates

In this subsection we provide indicative estimates of the significance of the auction cycles for the public budget and how this significance is affected by the central bank sovereign purchases. One can think of secondary market yield changes as being (close to) the "shadow" (i.e. unobserved) yield changes in the primary market. This is justified by the fact that the benchmark secondary market and the primary market instrument are always highly substitutable. In fact, because most auctions are reopenings, in most cases the pay-offs of the two instruments are identical. Hence, an increase in the secondary market yield prior to an auction would cause an increase in the yield at which the government issues its debt and, hence, it would imply a rise in the government's debt-servicing cost. Yield levels on secondary and primary market instruments may systematically differ, in particular because primary dealers may be rewarded by the DMO for their activities, which would tend to drive primary market yields below secondary market yields. However, because we work with yield *changes*, this effect should be eliminated and movements in secondary market yields around auction dates can be used to assess debt-servicing costs.

As an example, we provide estimates of the extra debt-servicing costs of French sovereign debt induced by the auction cycle and the savings on these additional debt-servicing costs produced by the ESCB sovereign debt purchases. The estimates are based on the unscaled cluster regression estimates reported in Column [1] of Table 7.

Throughout we assume that the domestic and foreign auction cycles are symmetric. For low-rated countries, the direct effect of the domestic auction dummies raises the yield at the auction by $8.16/2 = 4.08$ bps. A single foreign auction from a country in the low-rated cluster taking place on the same day as the domestic auction raises the auction yield by $2.83/2 = 1.42$ bps. Since the start of the APP, the average auction size of French 10-year debt equals €4534 million. Hence, the domestic auction cycle raises annual debt servicing costs by €4534 million times 4.08 bps, which is about €1.85 mln, while the foreign auction raises these by about €0.64 mln. This might seem small, but over the life-time of the bond these costs become non-negligible. Taking the example in Beetsma et al. (2016), with a 5-year average duration of a typical 10-year bond, over the bond's entire life the average additional cost (holding constant market volatility and ESCB debt purchases) amounts to €9.25 mln (€3.21 mln) for the domestic (foreign) cycle. Aggregating over the average number of French auctions in a given year (twelve), these amounts add up to €111 mln due to the domestic auction cycle and to €38 mln due to the foreign auction cycle (assuming a domestic auction is always accompanied by a single foreign auction on the same day and no other foreign auctions take place in the event window of the domestic auction), respectively.

The budgetary consequences of an increase in market volatility and the sovereign debt purchases can be assessed with a similar calculation.[35] In all the calculations we take Germany as the high-rated country and France as the low-rated country. For the spillover effects we focus on those arising from Italian auctions. The back-of-the-envelope estimates are given in Table 8. Empty cells reflect the fact that the coefficient estimates in the underlying regression are insignificant. The column "All issues in a year" aggregates the additional lifetime debt-servicing costs for the average annual number of 10-year domestic auctions.

So far, in the calculation of the spill-over effects, we assumed that a domestic auction was accompanied by a single foreign auction happening on the same day. However, our underlying regression equation aggregates the interaction of the coefficient estimates with all foreign auction dummies in a 10-day window around the domestic auction. To estimate the foreign spill-over on domestic debt-servicing costs, we need to take account of the window and the chance of the occurrence of one or more foreign auctions on each of the days in the window. This is what the last block of Table 8, denoted by $\widetilde{ACF}$, does in reporting the average impact of foreign auctions on domestic debt-servicing costs. As most spillover effects from the high-rated cluster onto the low-rated cluster are insignificant, we only account for spillover effects from the auctions by low-rated countries. The average number of auctions by other low-rated countries in the event window of a French auction turns out to be 1.26, which implies that the average number of foreign auctions per day in the event window is 0.126. Hence, the estimated spill-over from auctions by low-rated other countries onto the annual debt-servicing cost associated with a new French auction is 2.83/2 bps $\times 0.126 \times$€4534 mln

[35] These components are calculated under the assumption of a one standard deviation increase in market volatility and an amount of net sovereign debt purchases equal to its mean value. To be precise, a one standard deviation in market volatility magnifies the annual debt-servicing costs by 8.69/2 bps $\times 1.04 \times$€4534 mln = €2.05 mln, while the average daily purchases lower it by 10.46/2 bps $\times 0.196 \times$€4534 mln = €0.46 mln.

is 80k.

Table 8: Estimates of Budgetary Effects

	C_1 Yearly	C_1 Lifespan	C_1 All issues in a year	C_2 Yearly	C_2 Lifespan	C_2 All issues in a year
AC				1.85	9.25	110.99
$\times VOL$				2.05	10.24	122.93
$\times \Delta DH$	−0.14	−0.70	−9.82	−0.46	−2.32	−27.89
$\times \Delta DH \times VOL$	−0.27	−1.33	−18.65			
$\times Mkt$	−0.54	−2.68	−37.46			
ACF	0.39	1.97	27.59	0.64	3.21	38.49
$\times VOL$	0.73	3.64	50.96	1.46	7.32	87.84
$\times \Delta DH$	−0.08	−0.39	−5.41	−0.27	−1.33	−15.92
$\times \Delta DH \times VOL$	−0.29	−1.44	−20.13	−0.18	−0.92	−11.06
$\times Mkt$	−0.72	−3.62	−50.75			
$\widetilde{ACF}$	0.07	0.36	5.05	0.08	0.40	4.85
$\times VOL$	0.13	0.67	9.33	0.18	0.92	11.07
$\times \Delta DH$	−0.01	−0.07	−0.99	−0.03	−0.17	−2.01
$\times \Delta DH \times VOL$	−0.05	−0.26	−3.68	−0.02	−0.12	−1.39
x Mkt	−0.13	−0.66	−9.29			

Notes: (i) The numbers in the panel under C_1 are based on Germany, with column "All issues in a year" based on annually 14 issues of 10-year debt, and those in the panel under C_2 are based on France, with column "All issues in a year" based on annually 12 issues of 10-year debt. (ii) Numbers are in millions of euro. (iii) Empty cells reflect insignificant estimates of the coefficients the underlying regression. (iv) The numbers in the block ACF are based on the assumption of a single low-rated foreign auction on the same day as the domestic auction and no foreign low-rated auction on the other days in the event window of the domestic auction. (v) The numbers in the block $\widetilde{ACF}$ are based on the average number of foreign auctions by low-rated countries in the event window of the domestic auction (for Germany 1.83 and for France 1.26) and the assumption that those foreign auctions are evenly spread over the event window.

Our estimates suggest that the precise timing of the auctions and the within-year allocation for a given amount of debt to be placed in a year may matter for the debt-servicing costs. Auction dates tend to be fixed well in advance, while the amount to be issued at a given auction is usually announced only a few business days before the auction takes place. Obviously, cancelling an auction on short notice, because of market circumstances, would be a bad signal to investors. However, the DMO can limit the issue size when market circumstances are less favourable than normal. In fact, by limiting the size of the current issue (and placing more debt at a later moment) the DMO would not only limit debt-serivcing costs, but it would also reduce the risk of a failed auction in which not all the debt is placed. In addition, debt-servicing costs may be limited by coordination of the auction calendars among the Eurozone Member States, such that their auctions are scheduled with sufficient spacing in time. Finally, our results indicate that, even though the ESCB aims at limiting the market impact of its asset purchasing policy, its purchases do help in stabilizing bond price movements around auction dates.

7 Conclusion

This paper has investigated the presence of auction cycles associated with new Eurozone public debt issues and how these cycles are affected by the ECB's asset purchasing programs. To this end, we first develop a theoretical model that allows for a direct yield effect of central bank secondary-market interventions and a yield effect resulting from the interaction of these interventions with market volatility. Then, using a sample of the largest Eurozone debt-issuing countries, we find quite strong empirical evidence for the theoretical predictions of our model. We confirm the existence of domestic and foreign auction cycles, as well as the role of volatility strengthening these cycles. Most importantly, we find that larger sovereign purchases by the ESCB exert a stronger direct dampening effect on the auction cycles. The purchases also ameliorate the effect of market volatility on the auction cycles. These effects tend to be particularly strong for the countries with a relatively low credit rating and during the APP period. We also show that auction cycles can have a non-negligible effect on debt-servicing costs, which in turn can be reduced to a non-negligible extent by the central bank sovereign debt purchases.

Our estimates yield some potentially relevant conclusions for policy makers. First, in view of the presence of foreign auction cycles, DMOs in the Eurozone might save costs by coordinating the timing of their auctions, so that these are spread as much as possible in time. Second, overall debt-servicing costs may be reduced by raising auction volumes in periods of low market volatility at the expense of smaller volumes when markets are turbulent.[36] However, the ESCB could reduce the need for such intertemporal shifts in debt placement if it were to concentrate its debt purchases in periods of high general market volatility. Such a policy may be compatible with the aim of limiting disturbances to the markets if is conditioned purely on general (eurozone-wide) market circumstances and ignores the specific timing of sovereign debt auctions. Finally, notwithstanding its aim of limiting market disturbances, the ESCB purchases do help in stabilizing domestic and foreign bond price movements around auction dates.

Because the publicly available data on central bank debt holdings are only available at a relatively low frequency, we have to make an assumption about the allocation of APP activity within a given month. This limitation is unfortunate, because the absence of daily purchase data prevents us from capturing the exact timing of the purchases when this information is particularly useful. The fact that our estimates point to a role for central banks in diminishing auction cycles suggests that further investigation with more granular data is worthwhile, once such data become available or once information becomes available that allows one to infer central bank intervention activity with more precision.

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[36] Casual observation suggests that this indeed happens - see the Financial Times (October 11, 2018), which reports on a recent Italian auction of €6.5 bln that took place under relatively adverse circumstances, quoting Chiara Cremonesi, a strategist at UniCredit, that “this is a low amount and reflects the Treasury’s conservative attitude in the current volatile market”. See `https://www.ft.com/content/9a026742-cd39-11e8-b276-b9069bde0956`.

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9 Appendix (NOT for publication): Model Extended with Optimizing Secondary-Market Participants

In this appendix, we extend the model in the main text by including optimizing investors who trade only in the secondary market (henceforth referred to as "secondary-market traders"), and not in the primary market. We denote variables pertaining to secondary-market traders by subscript "s". We assume that they have the same innate degree of risk aversion as the primary market dealers. Hence, we can write the demand in the secondary market as:

$$X_s = \frac{1}{\eta} W_s \Sigma_{2^{nd}}^{-1} \left(\mathbb{E} \begin{bmatrix} \tilde{F}_{do} \\ \tilde{F}_{fo} \end{bmatrix} - \begin{bmatrix} P_{do} \\ P_{fo} \end{bmatrix} \right)$$

where $\Sigma_{2^{nd}} \equiv \begin{bmatrix} \sigma_{do}^2 & \rho_{do,fo}\sigma_{do}\sigma_{fo} \\ \rho_{do,fo}\sigma_{do}\sigma_{fo} & \sigma_{fo}^2 \end{bmatrix}$ is the variance-covariance matrix of all instruments traded on the secondary market, but not on the primary market. Aggregating demand yields:

$$\begin{bmatrix} \bar{X}_d - X_{E,d} \\ \bar{X}_f - X_{E,f} \end{bmatrix} = \frac{1}{\eta} \left(\begin{bmatrix} W_d \Sigma_{d,d}^{-1} & 0 \\ 0 & W_f \Sigma_{f,f}^{-1} \end{bmatrix} + W_g \Sigma^{-1} + W_s \underbrace{\begin{bmatrix} (\Sigma_{2^{nd}}^{-1})_{1,1} & 0 & (\Sigma_{2^{nd}}^{-1})_{1,2} & 0 \\ 0 & 0 & 0 & 0 \\ (\Sigma_{2^{nd}}^{-1})_{2,1} & 0 & (\Sigma_{2^{nd}}^{-1})_{2,2} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}}_{=\Sigma_{2^{nd}}^{-1} \otimes ee'} \right) \left(\mathbb{E}\left[\tilde{F}\right] - P \right)$$

where $e = [1, 0]^\top$. Assuming equilibrium in the sovereign bond markets (equating supply and demand) and solving for the price vector gives:

$$P = \mathbb{E}\left[\tilde{F}\right] - \eta \left(\begin{bmatrix} W_d \Sigma_{d,d}^{-1} & 0 \\ 0 & W_f \Sigma_{f,f}^{-1} \end{bmatrix} + W_g \Sigma^{-1} + W_s \left(\Sigma_{2^{nd}}^{-1} \otimes ee' \right) \right)^{-1} \begin{bmatrix} \bar{X}_d - X_{E,d} \\ \bar{X}_f - X_{E,f} \end{bmatrix}$$

Factor out Σ:

$$P = \mathbb{E}\left[\tilde{F}\right] - \eta \left(\begin{bmatrix} W_d I_2 & W_f \Sigma_{d,f} \Sigma_{f,f}^{-1} \\ \Sigma_{f,d} \Sigma_{d,d}^{-1} & W_f I_2 \end{bmatrix} + W_g I_4 + W_s \Sigma \left(\Sigma_{2^{nd}}^{-1} \otimes ee' \right) \right)^{-1} \Sigma \begin{bmatrix} \bar{X}_d - X_{E,d} \\ \bar{X}_f - X_{E,f} \end{bmatrix}$$

Rewrite:

$$P = \mathbb{E}\left[\tilde{F}\right] - \eta \left(A + B\right)^{-1} \Sigma \begin{bmatrix} \bar{X}_d - X_{E,d} \\ \bar{X}_f - X_{E,f} \end{bmatrix}$$

where $A \equiv \begin{bmatrix} \left(W_d + W_g\right) I_2 & W_f \beta_{d,f} \\ W_d \beta_{f,d} & \left(W_f + W_g\right) I_2 \end{bmatrix}$, with $\beta_{d,f} = \Sigma_{d,f} \Sigma_{f,f}^{-1}$ and $\beta_{f,d} = \Sigma_{f,d} \Sigma_{d,d}^{-1}$, and

$$B \equiv W_s \Sigma \left(\Sigma_{2^{nd}}^{-1} \otimes ee' \right) = W_s \begin{pmatrix} 1 & 0 & 0 & 0 \\ \frac{\left(\sigma_{dn,fo}\sigma_{do,fo} - \sigma_{do,dn}\sigma_{fo}\right)}{\sigma_{do,fo}^2 - \sigma_{do}\sigma_{fo}} & 0 & \frac{\left(\sigma_{dn,fo}\sigma_{do} - \sigma_{do,dn}\sigma_{do,fo}\right)}{\sigma_{do}\sigma_{fo} - \sigma_{do,fo}^2} & 0 \\ 0 & 0 & 1 & 0 \\ \frac{\left(\sigma_{do,fo}\sigma_{fo,fn} - \sigma_{do,fn}\sigma_{fo}\right)}{\sigma_{do,fo}^2 - \sigma_{do}\sigma_{fo}} & 0 & \frac{\left(\sigma_{do,fn}\sigma_{do,fo} - \sigma_{do}\sigma_{fo,fn}\right)}{\sigma_{do,fo}^2 - \sigma_{do}\sigma_{fo}} & 0 \end{pmatrix}$$

Using the results of Miller (1981) for the inversion of the sum of two matrices where $Rank\left(A\right) = 4$ and $Rank\left(B\right) = 2$.[37]

$$\left(A + B\right)^{-1} = C^{-1} \left(I - \frac{1}{1 + tr\left(C^{-1}E_2\right)} E_2 C^{-1} \right)$$

where $C^{-1} = A^{-1} - 1/\left(1 + tr\left(A^{-1}E_1\right)\right) A^{-1} E_1 A^{-1} = A^{-1}\left(I - 1/\left(1 + tr\left(A^{-1}E_1\right)\right) E_1 A^{-1}\right)$, and $B = E_1 + E_2$ are a non-unique decomposition of B into two rank 1 matrices E_1 and E_2. In what follows we take E_1 a matrix filled with zeroes except that the first column is replaced by the first column of B, while E_2 is a matrix filled with zeroes except that the

[37]Miller (1981) proves that $\left(A + B\right)^{-1} = C^{-1} - 1/\left(1 + tr\left(C^{-1}E_2\right)\right) C^{-1} E_2 C^{-1} = C^{-1}\left(I - 1/\left(1 + tr\left(C^{-1}E_2\right)\right) E_2 C^{-1}\right)$, where $C^{-1} = A^{-1} - 1/\left(1 + tr\left(A^{-1}E_1\right)\right) A^{-1} E_1 A^{-1} = A^{-1}\left(I - 1/\left(1 + tr\left(A^{-1}E_1\right)\right) E_1 A^{-1}\right)$, and $B = E_1 + E_2$ a non-unique decomposition of B into two rank 1 matrices E_1 and E_2.

third column is replaced by the third column of B. We have that

$$\begin{aligned} tr\left(C^{-1}E_2\right) &= tr\left(A^{-1}\left(I - \frac{1}{1+tr\left(A^{-1}E_1\right)}E_1A^{-1}\right)E_2\right) \\ &= tr\left(A^{-1}E_2\right) - \frac{1}{1+tr\left(A^{-1}E_1\right)}tr\left(A^{-1}E_1A^{-1}E_2\right) \\ &= tr\left(A^{-1}E_2\right) - \frac{1}{1+tr\left(A^{-1}E_1\right)}tr\left(A^{-1}A^{-1}\underbrace{E_1E_2}_{=0}\right) \\ &= tr\left(A^{-1}E_2\right) \end{aligned}$$

Denote $\frac{1}{1+tr\left(A^{-1}E_1\right)} \equiv g$ and $\frac{1}{1+tr\left(A^{-1}E_2\right)} \equiv h$, then:

$$\begin{aligned} (A+B)^{-1} &= C^{-1}\left(I - hE_2C^{-1}\right) \\ &= A^{-1}\left(I - gE_1A^{-1}\right)\left(I - hE_2A^{-1}\left(I - gE_1A^{-1}\right)\right) \\ &= A^{-1}\left(I - gE_1A^{-1}\right)\left(I - hE_2A^{-1} + ghE_2A^{-1}E_1A^{-1}\right) \\ &= A^{-1}\left(I - hE_2A^{-1} + ghE_2A^{-1}E_1A^{-1} - gE_1A^{-1} + ghE_1A^{-1}E_2A^{-1} - g^2hE_1A^{-1}E_2A^{-1}E_1A^{-1}\right) \\ &\equiv A^{-1}Z \end{aligned}$$

Hence, we can write

$$P = \mathbb{E}\left[\tilde{F}\right] - \eta A^{-1}Z\Sigma \begin{bmatrix} \bar{X}_d - X_{E,d} \\ \bar{X}_f - X_{E,f} \end{bmatrix}$$

The inversion of the partitioned matrix A^{-1} follows from the results of Bierens (2014), and is given by:

$$A^{-1} = \begin{bmatrix} \left[\left(W_d + W_g\right)I - \frac{W_dW_f}{W_f+W_g}\beta_{d,f}\beta_{f,d}\right]^{-1} & \frac{W_f}{W_d+W_g}\beta_{d,f}\left[\left(W_f + W_g\right)I - \frac{W_dW_f}{W_d+W_g}\beta_{f,d}\beta_{d,f}\right]^{-1} \\ \frac{W_d}{W_f+w_g}\beta_{f,d}\left[\left(W_d + W_g\right)I - \frac{W_dW_f}{W_f+W_g}\beta_{d,f}\beta_{f,d}\right]^{-1} & \left[\left(W_f + W_g\right)I - \frac{W_dW_f}{W_d+W_g}\beta_{f,d}\beta_{d,f}\right]^{-1} \end{bmatrix}$$

Compared to our initial model the solution for the asset prices contains a dampening factor Z, because of the additional demand from the secondary market traders. In order to obtain an expression that can be interpreted in more detail, we would need to simplify Z further.

Table 9: Parameter Calibration.

Parameter	Value
η	8
W_d	4
W_f	5
W_g	6
W_2	4
$\sigma^2_{d,o}$	1.5
$\sigma^2_{d,n}$	1.5
$\sigma^2_{f,o}$	1.2
$\sigma^2_{f,n}$	1.2
$\sigma^2_{(d,o),(d,n)}$	0.8
$\sigma^2_{(d,o),(f,o)}$	0.5
$\sigma^2_{(d,o),(f,n)}$	0.3
$\sigma^2_{(d,n),(f,o)}$	0.3
$\sigma^2_{(d,n),(f,n)}$	0.4
$\sigma^2_{(f,o),(f,n)}$	0.75

Unfortunately, we are unable to do so, and, hence, we turn to a numerical evaluation of the effects of a new debt issue and how these effects are influenced by the size α of the ESCB secondary-market intervention. Table 9 depicts the parameter calibration. Figure 7 displays the effect of a new debt issue on the price of the existing bond for the cases without and with secondary-market traders. We observe that in the latter case the negative price effect of the auction is smaller for each combination of α and γ. As before, with secondary-market traders, a higher value of γ produces a larger price fall, while a higher value of α results in a smaller price fall. Finally, we notice that the negative slope in γ is smaller at higher values of α. In other words, Hypotheses 1a-d continue to hold.

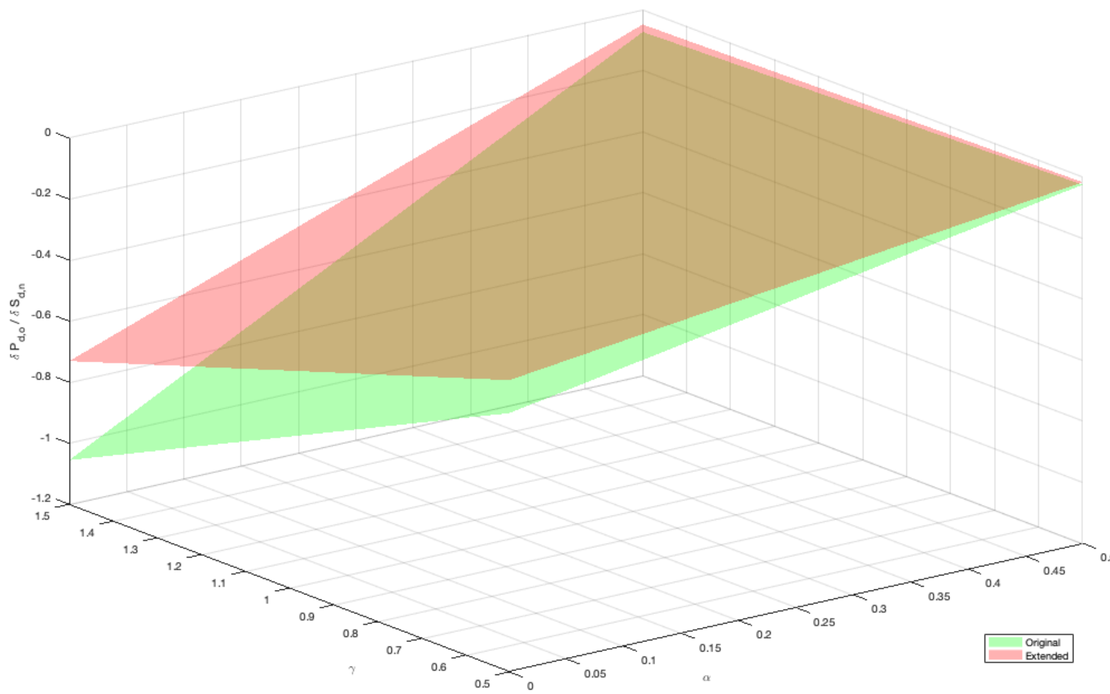

Figure 7: Numerical Results.

10 Additional Tables

Table 10: Correlations in Secondary-Market Yield Movements.

		AT	BE	DE	ES	FI	FR	IT	NL	PT
Full-Sample	AT	1.00								
	BE	0.75	1.00							
	DE	0.74	0.67	1.00						
	ES	0.44	0.59	0.30	1.00					
	FI	0.60	0.56	0.70	0.29	1.00				
	FR	0.78	0.81	0.77	0.52	0.62	1.00			
	IT	0.41	0.58	0.29	0.79	0.28	0.52	1.00		
	NL	0.77	0.76	0.86	0.44	0.68	0.87	0.42	1.00	
	PT	0.19	0.27	0.13	0.39	0.14	0.22	0.37	0.18	1.00
Pre-APP period	AT	1.00								
	BE	0.81	1.00							
	DE	0.78	0.84	1.00						
	ES	0.68	0.82	0.72	1.00					
	FI	0.54	0.59	0.62	0.52	1.00				
	FR	0.76	0.88	0.83	0.82	0.58	1.00			
	IT	0.63	0.76	0.69	0.82	0.50	0.76	1.00		
	NL	0.77	0.89	0.85	0.83	0.59	0.93	0.78	1.00	
	PT	0.45	0.59	0.43	0.69	0.34	0.53	0.64	0.52	1.00
APP period	AT	1.00								
	BE	0.68	1.00							
	DE	0.69	0.46	1.00						
	ES	0.24	0.43	-0.05	1.00					
	FI	0.73	0.54	0.87	0.08	1.00				
	FR	0.81	0.74	0.68	0.28	0.71	1.00			
	IT	0.25	0.46	-0.04	0.77	0.08	0.33	1.00		
	NL	0.76	0.58	0.89	0.10	0.87	0.76	0.11	1.00	
	PT	0.07	0.14	-0.03	0.29	0.03	0.07	0.28	-0.01	1.00

Note: see Notes to Table 2.

Table 11: Cluster-Specific Effects for the APP period, Instrumental Variables.

	[1]		[2]		[3]	
	C_1	C_2	C_1	C_2	C_1	C_2
AC	-0.67	7.86^{***}	-1.64	6.48^{**}	-1.73	7.50^{**}
$\times VOL$	-1.45	8.80^{***}	-2.78^{***}	6.57^{*}	-3.50^{***}	7.79^{**}
$\times \Delta DH$	-4.91^{**}	-14.66	-2.56	-1.76	-0.24	-3.11
$\times \Delta DH \times VOL$	-5.36	-5.40	8.03	6.08	6.87	-0.81
$\times MktDepth$	-1.83^{***}	0.26				
ACF_{C_1}	-0.74^{*}	-0.86	0.02	0.52	-0.19	1.65
$\times VOL$	-0.52	-1.65	0.35	3.91^{***}	-0.58	-2.60^{*}
$\times \Delta DH$	-3.37^{*}	-2.12	-7.77^{**}	-1.91^{*}	-2.15^{*}	0.52
$\times \Delta DH \times VOL$	0.09	15.34^{*}	-8.17^{***}	-10.95^{***}	0.51	9.75^{**}
$\times MktDepth$	0.05	3.63				
ACF_{C_2}	1.99^{***}	2.62^{***}	1.72	4.03^{*}	0.77^{*}	4.28^{*}
$\times VOL$	3.68^{***}	6.03^{***}	-2.70^{*}	6.56^{**}	3.40^{***}	7.18^{***}
$\times \Delta DH$	1.47	-9.56^{**}	-0.92	-8.23	-1.08^{**}	-3.42^{**}
$\times \Delta DH \times VOL$	-2.87	-1.41	18.87^{**}	-2.05	-1.97^{***}	0.26
$\times MktDepth$	-2.26^{***}	1.73				
Δ Eonia	-0.18		-0.70		-0.65	
Δ Eurostoxx50	-0.35^{***}		-0.37^{***}		-0.34^{***}	
Δ Eurostoxx Bank	-0.03		-0.02		-0.03	
Δ VIX	-0.01		-0.01		-0.01	
BB	1.92^{*}		2.04^{**}		2.03^{**}	
R^2_{adj}	0.05		0.05		0.05	
T	1949		1949		1949	
N	9		9		9	

Notes: (i) one, two, and three asterisks indicate the 10, 5 and 1% significance levels, respectively. (ii) ACF_{C_i} is the effect of foreign auctions of countries in cluster i, C_i. (iii) Column [1] reports the cluster estimates, Columns [2] and [3] the estimates when debt purchases are scaled by outstanding debt and GDP, respectively.