Does a Big Bazooka Matter? Central Bank Balance-Sheet Policies and Exchange Rates*

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Abstract

We estimate the effects of quantitative easing (QE) measures by the ECB and the Federal Reserve on the US dollar-euro exchange rate at frequencies and horizons relevant for policymakers. To do so, we derive a theoretically-consistent local projection regression equation from the standard asset pricing formulation of exchange rate determination. We then proxy unobserved QE shocks by future changes in the relative size of central banks' balance sheets, which we instrument by QE announcements in two-stage least squares regressions in order to address their endogeneity. Deriving the local projection regression equation from a structural equation for the exchange rate disciplines the empirical specification we bring to the data, for example by pointing to the possible sources of endogeneity and guiding the choice of control variables. We also pay great attention to model specification tests, including instrument validity and power. We find that QE measures have large and persistent effects on the exchange rate. For example, our estimates imply that the ECB's APP program which raised the ECB's balance sheet relative to that of the Federal Reserve by 35 percentage points between March 2015 and the end of 2016 depreciated the euro vis-à-vis the US dollar by 20%. Regarding transmission channels, we find that a relative QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve depreciates the US dollar-euro exchange rate by reducing euro-dollar short-term money market rate differentials, by widening the cross-currency basis and by eliciting adjustments in currency risk premia. Quantitatively, the largest contribution to the exchange rate effects stems from changes in current and future expected interest rate differentials, which reflects the "signalling" channel of QE.

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1 Introduction

Since the onset of the global financial crisis in 2008, central banks around the world have engaged in a number of unprecedented and unconventional monetary policy interventions. In particular, central banks have deployed quantitative easing (QE) measures as an additional policy tool when interest rates reached their lower bound. For instance, Figure 1 shows that the Federal Reserve was early in purchasing sizeable amounts of private and government securities, which resulted in a dramatic expansion of its balance sheet between 2008 and 2012. The ECB initially implemented more modest asset purchase programs, but greatly expanded its provision of liquidity to the banking sector far beyond standard short-term maturities, especially after the second half of 2011. By March 2012, the nominal size of the ECB's balance sheet was similar to that of the Federal Reserve. Then, between March 2012 and the start of 2015, the asset purchases under the Federal Reserve's QE3 program again doubled the Federal Reserve's balance sheet relative to that of the ECB. Finally, in March 2015 the ECB embarked on a comprehensive program of private and public asset purchases, which returned the size of its balance sheet close to that of the Federal Reserve by the end of 2017.

The exchange rate has been at the center stage of the discussion about the effectiveness, transmission channels and the spillovers from QE (see, for example, Mantega, 2010; Rajan, 2013; Bernanke, 2015; Bruno and Shin, 2015a,b). That monetary policy actions which alter the size of the central bank's balance sheet and thereby the (relative) monetary base may affect the currency's international value is not a new topic, as it has already been discussed in the context of the monetary theory of the exchange rate and the effectiveness of exchange rate interventions (Taylor and Sarno, 2001). And indeed, Figure 1 documents that there has been a correlation between the announcements of QE measures, the relative balance sheet of the ECB and the Federal Reserve, and the US dollar-euro exchange rate. In particular, central banks' balance sheets tended to expand and the corresponding currency to depreciate after announcements of QE measures. These correlations are of course silent about causality, and can thereby not be referred to in order to prove the effectiveness or transmission channels of QE measures. Against this background, a large literature that is concerned with assessing the effects of QE measures has emerged.[1] However, the bulk of this literature has considered the high-frequency and short-term effects of QE measures, typically by means of event studies that focus on a narrow time window around their announcement. This approach is not informative regarding the persistence of the effects and the transmission channels of QE beyond the very short-term, and thereby of little help for central banks in understanding whether QE is an effective policy instrument.

Some work exists that has explored the effects of QE at lower frequencies and longer horizons.

[1] The literature has become too voluminous to do equal justice to all relevant contributions. For surveys of the literature see Bhattarai and Neely (2016) and Borio and Zabai (2016).

Early studies are Kapetanios et al. (2012) as well as Baumeister and Benati (2013), who study the effects of QE in the US and the UK, respectively, considering monthly VAR models and conceiving QE as shocks to the government bond spread. Gambacorta et al. (2014) bring the monthly VAR framework to a panel context for eight advanced economies in order to address the short sample period, conceiving QE as shocks to the central bank balance sheet. Weale and Wieladek (2016) focus on the US and the UK and consider the announced amounts under the central banks' asset purchase programs in order to proxy QE shocks in monthly VAR models. Wu and Xia (2016) study the effects of unconventional monetary policy more generally, using the shadow federal funds rate in a VAR model for the US. Meinusch and Tillmann (2016) consider a monthly QualVAR model for the US in which QE announcements proxy an unobserved propensity for QE. Much less work has so far been done on the euro area. Altavilla et al. (2016) study the effects of the OMT announcements in counterfactual simulations in a VAR framework, calibrating the OMT shock based on the effect on government bond yield spreads estimated in a high-frequency event study. Boeckx et al. (2017) estimate monthly VAR models, again proxying QE shocks by the central bank balance sheet. All of these studies consider the effects of QE on output and inflation. Only Boeckx et al. (2017) investigate in more depth the transmission channels of QE by adding a few variables one at a time to their baseline VAR model. Most importantly, *none* of these studies investigates the effects of QE on the exchange rate, which is surprising given its prominence in the debate about the effectiveness of QE, its transmission channels and spillovers.

Our paper fills this gap. We estimate the effects of QE on the exchange rate at frequencies and time horizons that are relevant for policymakers, and we explore the transmission channels through which they materialise. We focus on the exchange rate of the US dollar against the euro, as the ECB and the Federal Reserve have been carrying out the largest QE programmes after the global financial crisis, and as this is the world's most liquid currency pair. As the dollar-euro exchange rate is a relative price, in our analysis we consider the size of the ECB's balance sheet *relative* to that of the Federal Reserve as well as QE announcements by both the ECB and the Federal Reserve. Our findings suggest that QE measures have large and persistent effects on the exchange rate. For example, our estimates imply that the ECB's APP program which raised the ECB's balance sheet relative to that of the Federal Reserve by 35 percentage points between March 2015 and the end of 2016 depreciated the euro vis-à-vis the US dollar by 20%. Regarding the transmission channels, we find that a relative QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve reduces the euro-dollar short-term money market interest rate differential, reflecting expectations of further monetary policy accommodation in the short and medium term. Moreover, we find that QE shocks exacerbate limits to arbitrage in foreign exchange markets, as they widen CIP deviations reflected in the cross-currency basis. Quantitatively, our results suggest that the largest contribution to the exchange rate effects of QE stems from changes in current and future expected interest rate differentials, which reflects the "signalling" channel of monetary policy (see Woodford, 2012).[2] Finally, we find that changes in risk premia in foreign exchange markets play an important role in the transmission of QE shocks to the exchange rate. Focusing on the ECB, we also find that QE measures have considerable effects on other financial variables. Specifically, our results suggest that the ECB's purchases under the APP program between March 2015 and the end of 2016 lowered the euro area ten-year sovereign bond yield by about one percentage point and raised equity prices by a cumulative 20%.

We arrive at these conclusions adopting an empirical approach that draws on elements from several strands of the literature. Borrowing from the news shocks literature (Schmitt-Grohe and Uribe, 2008), we conceive QE measures that are announced in period t as shocks which materialise in period t but which are anticipated by agents to affect central banks' balance sheets only in future periods $t+m$, $m = 1, 2, \ldots, M$. We then show that while these QE shocks are unobserved by the econometrician they can be proxied by future changes in central banks' balance sheets. In turn, we show that the endogeneity of the future changes in central banks' balance sheets can be accounted for by using announcements of QE measures as instruments. We consider QE *shocks* rather than *announcements* as the main variable of interest in our empirical framework because this allows us to come up with a quantitative assessment of the overall effects of the ECB's and the Federal Reserve's major QE programs on the exchange rate. In particular, our framework allows us to determine an elasticity that reflects the change in the exchange rate that is implied by a QE measure that changes the relative central bank balance sheet by a given magnitude.

More technically, we estimate the effects of QE on the dollar-euro exchange rate using local projections (Jorda, 2005). We derive a theoretically-consistent local projection regression equation from the standard asset pricing formulation of exchange rate determination, according to which the spot exchange rate is given by current and future expected fundamentals. Specifically, the local projection regression for the exchange rate at horizon h is implied by the difference between the uncovered interest rate parity (UIP) conditions for periods $t+h$ and $t-1$. In order to address the endogeneity of the central banks' relative balance sheet—which we use as proxy for the unobserved QE shocks—in the local projection regression equation, we exploit announcements of ECB and Federal Reserve QE measures as instruments in two-stage least squares regressions (Jorda et al., 2015; Ramey and Zubairy, forthcoming). Deriving the local projection regression equation from a structural equation for the exchange rate disciplines the empirical specification we bring to the data, for example by pointing to the possible sources of

[2] Our results cannot be read as implying that signalling has been the most important transmission channel for the effects of QE *in general*, i.e. to variables beyond the exchange rate. In fact, we find that QE lowers the term premium, implying transmission to domestic variables through duration extraction.

endogeneity, guiding the choice of control variables and their timing. We also pay great attention to model specification tests, including instrument validity and power. Another appealing feature of our empirical framework is that it allows us to take into account *future* changes in central banks' balance sheets in order to proxy QE shocks; in contrast, the existing literature discussed above typically conceives QE shocks as contemporaneous changes in the balance sheet. Given that the exchange rate is a forward-looking variable, we believe that our framework is better suited to assess the relevant effects of QE. Finally, we explore a battery of robustness checks related to variations of the identification of QE shocks, various aspects of the regression specification and data frequency.

The paper is organized as follows. In Section 2 we review standard exchange rate determination according to asset pricing theory, and we derive the local projection equation for the exchange rate. Then, in Section 3 we describe the empirical specification of the local projection regression, followed by our results in Section 4. Section 5 presents robustness checks, and Section 6 concludes.

2 An framework for the assessment of the effects of QE on the exchange rate

In this section we motivate the local projection regression equation for the exchange rate that we will use in order to estimate the effects of QE measures. To do so, we first draw on textbook asset pricing theory and review exchange rate determination in the presence of frictions that may give rise to deviations from CIP. The associated UIP condition implies that the value of the spot exchange rate in period t is equal to the un-discounted sum of current and future expected fundamentals, i.e. interest rate differentials, CIP deviations and currency risk premia up to horizon T, as well as the expected exchange rate at horizon T. Finally, we show that we can estimate the effects of QE shocks on the exchange rate at horizon h based on a theoretically-consistent local projection regression equation derived as the difference between the UIP conditions for periods $t+h$ and $t-1$.

2.1 Exchange rate determination and CIP deviations

Consider an investor whose relevant nominal discount factor is expressed in US dollars ("American" investor), $\mathcal{D}_t^{\$}$.[3] Under standard conditions, the relation between $\mathcal{D}_t^{\$}$ and the one-period

[3]Under general conditions, the stochastic discount factor is equal to the ratio of Lagrange multipliers on the agent's future and current budget constraint, i.e., her marginal value of wealth (see Lucas, 1978). The nominal discount factor is not necessarily a function of consumption growth only. For instance, with Epstein-Zin-Weil preferences, it is a nontrivial function of wealth growth itself.

nominally risk-free US dollar nominal interest rate $R_t^{\$}$ is then given by:

$$1 = E_t\left(\mathcal{D}_{t+1}^{\$}\right) R_t^{\$}. \tag{1}$$

Equation (1) implies that one dollar today has to be equal to the certain dollar amount $R_t^{\$}$ in period $t+1$, appropriately discounted by the expected marginal value of wealth across the two periods. Similarly, denoting by $R_t^{€}$ the one-period risk-free euro nominal rate, by $F_{t,t+1}$ the forward dollar price of one euro, and by S_t the spot exchange rate expressed in the amount of dollars per euro, the investor would price the nominally safe investment of one dollar today into $1/S_t$ euro yielding the safe dollar payoff $F_{t,t+1}R_t^{€}$ in period $t+1$ as:

$$1 = E_t\left(\mathcal{D}_{t+1}^{\$}\right) \frac{F_{t,t+1}R_t^{€}}{S_t}. \tag{2}$$

More generally, if the investor is potentially borrowing constrained, the two Euler equations above read as follows:

$$1 \geq 1 - \lambda_t^{\$} = E_t\left(\mathcal{D}_{t+1}^{\$}\right) R_t^{\$}, \tag{3}$$

and

$$1 \geq 1 - \lambda_t^{€} = E_t\left(\mathcal{D}_{t+1}^{\$}\right) \frac{F_{t,t+1}R_t^{€}}{S_t}. \tag{4}$$

When $\lambda_t^{\$} = 0$, Equation (3) holds with equality and the investor is not facing a binding borrowing constraint at the desired level of investment in the dollar cash market. Even in the presence of borrowing constraints, this is the case when the desired investment is positive, i.e. the investor is saving. When $\lambda_t^{\$} > 0$, one dollar in period t is worth more than (the appropriately discounted value of) $R_t^{\$}$ in $t+1$. In the absence of borrowing constraints, the investor would borrow against future income until the value of one dollar in periods t and $t+1$ is equalised. Thus, $\lambda_t^{\$} \geq 0$ can be interpreted as the shadow value of borrowing one additional dollar.[4] The rationale for $\lambda_t^{€}$ is analogous, but refers to borrowing and saving in the synthetic risk-free dollar markets at the rate $\frac{F_{t,t+1}R_t^{€}}{S_t}$.

Combining Equations (3) and (4) implies the CIP condition:

$$R_t^{\$} = \frac{F_{t,t+1}R_t^{€}}{S_t} \cdot (1 - \lambda_t), \tag{5}$$

[4]We can also interpret λ_t^i as transaction costs. In this case, allocating one dollar to either strategy only translates into an effective investment of $1 - \lambda_t^i$ dollars. A key difference is that $\lambda_t^i > 0$ even when the investor is long.

where $\lambda_t \equiv 1 - \frac{1-\lambda_t^{\$}}{1-\lambda_t^{€}}$ represents CIP deviations.[5,6] In particular, in case $\lambda_t > 0$, meaning that $\lambda_t^{\$} > \lambda_t^{€} \geq 0$, we have that borrowing is more expensive in the synthetic dollar market at the rate $\frac{F_{t,t+1}R_t^{€}}{S_t}$ than in the cash market at the rate $R_t^{\$}$; this implies that dollar cash market borrowing constraints are tighter. Taking logs of Equation (5) yields:

$$r_t^{\$} \simeq r_t^{€} + f_{t,t+1} - s_t - \lambda_t, \tag{6}$$

where we have assumed that CIP deviations λ_t are small.[7] Notice that our definition of the CIP deviation implied by Equation (6), namely

$$\lambda_t \equiv r_t^{€} - \left(r_t^{\$} - f_{t,t+1} + s_t\right), \tag{8}$$

coincides with the market definition of the cross-currency basis, except for having the *opposite* sign (see, for example, Du et al., 2017).

As regards the pricing of the forward rate, arbitrage forces ensure that the one-period risk-adjusted expected return of investing in the dollar-euro forward market or in the dollar-euro spot market are the same, namely:

$$\frac{E_t\left(\mathcal{D}_{t+1}^{\$}\right)F_{t,t+1}}{S_t}R_t^{€} = \frac{E_t\left(\mathcal{D}_{t+1}^{\$}S_{t+1}\right)}{S_t}R_t^{€}. \tag{9}$$

Hence, we have the following relation between the forward and the expected spot exchange rate:

$$F_{t,t+1} = E_t\left(S_{t+1}\right) + \frac{Cov_t\left(\mathcal{D}_{t+1}^{\$}, S_{t+1}\right)}{E_t\left(\mathcal{D}_{t+1}^{\$}\right)}. \tag{10}$$

[5] In the Online Appendix we show that CIP deviations cannot arise because of counterparty risk in the forward market.

[6] The CIP condition could also be derived from the perspective of a euro area investor whose relevant nominal discount factor is $\mathcal{D}_t^{€}$ based on:

$$1 \geq 1 - \lambda_t^{€} = E_t\left(\mathcal{D}_{t+1}^{€}\right)R_t^{€},$$
$$1 \geq 1 - \lambda_t^{\$} = E_t\left(\mathcal{D}_{t+1}^{€}\right)\frac{S_t R_t^{\$}}{F_{t,t+1}}.$$

[7] Deviations from CIP could in principle also arise if the dollar or euro cash rates were not safe, say because of default risk, and if this risk was different across rates. In this case, the conditions under which the CIP condition was derived above would fail. Instead, one would have:

$$1 = E_t\left(\mathcal{D}_{t+1}^{\$}R_t^{€}\right)\frac{F_{t,t+1}}{S_t} = E_t\left(\mathcal{D}_{t+1}^{\$}R_t^{\$}\right). \tag{7}$$

In this case, arbitrage does not ensure anymore that the forward-spot discount is equal to the interest rate differential. However, several contributions have shown that interest rate default risk has not been a key source of CIP deviations recently (see, for example, Du et al., 2017).

Assuming log-normality and taking logs yields:

$$\begin{aligned} f_{t,t+1} &= E_t s_{t+1} + Cov_t\left(d^{\$}_{t+1}, s_{t+1}\right) + \frac{1}{2} Var_t\left(s_{t+1}\right) \\ &= E_t s_{t+1} + \pi_t. \end{aligned} \tag{11}$$

Taking into account Jensen's inequality (the term $\frac{1}{2}Var_t(s_{t+1})$), the forward rate exceeds (falls short of) the expected spot rate when the investor is willing to pay a positive (negative) premium. The latter is the case when the spot rate is expected to co-vary positively (negatively) with the investor's discount factor.[8]

Substituting the forward rate in Equation (11) in the CIP condition in Equation (6), we obtain the UIP condition:

$$s_t = E_t s_{t+1} + dr_t - \lambda_t + \pi_t, \tag{12}$$

where $dr_t \equiv r^{€}_t - r^{\$}_t$. Iterating forward Equation (12) for T periods yields:

$$s_t = E_t s_{t+T} + \sum_{j=0}^{T-1} E_t dr_{t+j} - \sum_{j=0}^{T-1} E_t \lambda_{t+j} + \sum_{j=0}^{T-1} E_t \pi_{t+j}, \tag{13}$$

which shows that the spot exchange rate in period t is determined by current and expected future fundamentals—i.e. interest rate differentials, risk premia, CIP deviations, and the expected value of the exchange rate at horizon T. Equation (13) implies that QE measures can impact the current value of the exchange rate only to the extent that they affect current and expected future fundamentals.

2.2 Deriving a local projection equation for the exchange rate

Consider the UIP condition in Equation (13) and subtract from both sides the corresponding equation lagged by one period:

$$\begin{aligned} s_t - s_{t-1} = &- dr_{t-1} + \lambda_{t-1} - \pi_{t-1} \\ &+ E_t s_{t+T} - E_{t-1} s_{t+T} + \sum_{j=0}^{T-1} \left(E_t dr_{t+j} - E_{t-1} dr_{t+j}\right) \\ &- \sum_{j=0}^{T-1} \left(E_t \lambda_{t+j} - E_{t-1} \lambda_{t+j}\right) + \sum_{j=0}^{T-1} \left(E_t \pi_{t+j} - E_{t-1} \pi_{t+j}\right). \end{aligned} \tag{14}$$

[8] Specifically, the premium π_t is positive if dollar depreciation against the euro (a higher S_{t+1}) is expected to go hand in hand with a higher marginal value of wealth (higher $\mathcal{D}^{\$}_{t+1}$). This means that the dollar currency risk of a nominally safe euro investment provides a hedge to the investor, who then requires compensation to hold the forward. Conversely, the premium π_t is negative when dollar depreciation is expected to be associated with a lower discount factor of the investor.

The terms in the second and third row involve differences between the same variables, but in terms of expectations formed in period t and $t-1$, respectively. Under rational expectations, these terms are functions of the structural shocks in period t, i.e. the vector of mutually uncorrelated white noise variables $\boldsymbol{\varepsilon}_t$ with $E_{t-1}(\boldsymbol{\varepsilon}_t) = 0$. Assuming linearity, we can replace the changes in expectations by the impact of structural shocks and write Equation (14) as:

$$s_t - s_{t-1} = \omega_{t-1,0} + \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_t, \tag{15}$$

where

$$\omega_{t-1,0} \equiv - dr_{t-1} + \lambda_{t-1} - \pi_{t-1}, \tag{16}$$

$$\begin{aligned} \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_t \equiv & E_t s_{t+T} - E_{t-1} s_{t+T} + \sum_{j=0}^{T-1} \left(E_t dr_{t+j} - E_{t-1} dr_{t+j} \right) \\ & - \sum_{j=0}^{T-1} \left(E_t \lambda_{t+j} - E_{t-1} \lambda_{t+j} \right) + \sum_{j=0}^{T-1} \left(E_t \pi_{t+j} - E_{t-1} \pi_{t+j} \right). \end{aligned} \tag{17}$$

Analogously, for the difference between the exchange rate in periods $t+h$ and $t-1$ we have:

$$s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_{t+h} + \boldsymbol{\alpha}_1' \boldsymbol{\varepsilon}_{t+h-1} + \ldots + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t, \tag{18}$$

where

$$\begin{aligned} \omega_{t-1,h} \equiv & - dr_{t-1} + \lambda_{t-1} - \pi_{t-1} \\ & - \sum_{j=1}^{h-1} E_{t-1} dr_{t+j-1} + \sum_{j=1}^{h-1} E_{t-1} \lambda_{t+j-1} - \sum_{j=0}^{h-1} E_{t-1} \pi_{t+j-1}. \end{aligned} \tag{19}$$

Taking expectations of Equation (18) as of period t yields:

$$E_t s_{t+h} - s_{t-1} = \omega_{h,t-1} + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t, \tag{20}$$

which shows that the coefficients $\boldsymbol{\alpha}_h$ represent the impulse response of the exchange rate at horizon h to the structural shocks $\boldsymbol{\varepsilon}_t$ in period t. We can estimate the coefficients $\boldsymbol{\alpha}_h$ by ordinary least squares from the regression

$$s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t + \nu_{t,h}, \tag{21}$$

where

$$\nu_{t,h} \equiv \sum_{j=0}^{h-1} \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_{t+h-j}, \tag{22}$$

as the structural shocks are white noise, satisfying $Cov(\nu_{t,h}, \boldsymbol{\varepsilon}_t) = Cov(\nu_{t,h}, \omega_{t-1,h}) = 0$.

2.3 Introducing QE shocks

In order to see how the local projection in Equation (21) can be used to estimate the effects of QE shocks specifically, partition the structural shocks into $\boldsymbol{\varepsilon}_t = (\varepsilon_t^{qe}, \boldsymbol{e}_t')'$; ε_t^{qe} is a QE shock and $\boldsymbol{e}_t$ includes all other structural shocks, such as conventional monetary policy shocks or money demand shocks. Notice that because the US dollar-euro exchange rate is a relative price, the term ε_t^{qe} should be interpreted as a *relative* QE shock, i.e. QE measures implemented by the ECB or the Federal Reserve and which affect the size of their relative balance sheet. Moreover, borrowing from the news shock literature (see, for example, Schmitt-Grohe and Uribe, 2008), we assume that ε_t^{qe} can be written as

$$\varepsilon_t^{qe} = \sum_{m=1}^{M} \eta_{t+m|t}, \tag{23}$$

where $\eta_{t+m|t}$ reflects the component of the QE shock that materialises in period t which affects the relative balance sheet only in period $t+m$.[9] Partitioning the vector of impulse response coefficients accordingly as $\boldsymbol{\alpha}_h = (\alpha_h^{qe}, \boldsymbol{a}_h')'$, we can then write the local projection for the exchange rate in Equation (21) as:

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=1}^{M} \eta_{t+m|t} \right) + \omega_{t-1,h} + \boldsymbol{a}_0' \boldsymbol{e}_t + \nu_{t,h}. \tag{25}$$

The intuition underlying Equation (25) is that because the exchange rate is a forward-looking asset price it will also respond to QE measures that are announced in period t but that will only be—and are anticipated by agents to be—implemented in period $t+m$ in the future.

2.4 Proxying QE shocks by future central bank balance sheet changes

Estimating the effects of QE measures in the euro area and the US on the dollar-euro exchange rate in Equation (25) is of course complicated by the fact that the QE shocks $\eta_{t+m|t}$ are unobserved by the econometrician. However, we can proxy these relative QE shocks by changes in the relative balance sheet. Specifically, assume that the relative balance sheet evolves according

[9] In general one would write

$$\varepsilon_t^{qe} = \sum_{m=1}^{M} \phi_m \eta_{t+m|t}. \tag{24}$$

We assume $\phi_m = 1$, $m = 0, 1, \ldots, M$ for simplicity.

to

$$\Delta BS_t = \delta_0 + \boldsymbol{\rho}' \boldsymbol{w}_{t-1} + \sum_{m=1}^{M} \eta_{t|t-m} + \boldsymbol{\delta}' \boldsymbol{e}_t, \tag{26}$$

where $\boldsymbol{w}_{t-1}$ in general includes macroeconomic and financial variables to which the central banks' balance sheets respond systematically as well as the lagged relative balance sheet.[10] We can substitute the anticipated QE shock $\eta_{t+m|t}$ in the local projection of the exchange rate in Equation (25) using Equation (26), namely

$$\eta_{t+m|t} = \Delta BS_{t+m} - \left(\delta_0 + \boldsymbol{\rho}' \boldsymbol{w}_{t+m-1} + \sum_{\substack{k=1 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \boldsymbol{e}_{t+m} \right),$$

to obtain

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=1}^{M} \Delta BS_{t+m} \right) + \omega_{t-1,h} - \alpha_h^{qe} \rho \sum_{m=1}^{M} \boldsymbol{w}_{t-1+m} + \widetilde{\delta}_0 + \zeta_{t,h}, \tag{27}$$

where

$$\zeta_{t,h} \equiv -\alpha_h^{qe} \boldsymbol{\delta}' \sum_{m=1}^{M} \boldsymbol{e}_{t+m} - \alpha_h^{qe} \sum_{m=1}^{M} \sum_{\substack{k=1 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{a}_0' \boldsymbol{e}_t + \nu_{t,h}. \tag{28}$$

In contrast to the existing literature on the effects of QE, an appealing feature of the framework in Equation (24) and eventually Equation (27) is that we take into account the component of QE shocks that is reflected in future changes in central banks' balance sheets. Given that the exchange rate is a forward-looking variable, we believe that this framework is better suited to assess the exchange rate effects of QE than the typical VAR framework used in the existing literature.

2.5 Two-stage least squares regression framework

Of course, the variable of interest in Equation (27), $\sum_{m=1}^{M} \Delta BS_{t+m}$, is endogenous due to its correlation with $\zeta_{t,h}$.[11] Intuitively, and as reflected in Equation (26), central banks' balance sheets change not only in response to QE shocks, but also because of non-QE shocks $\boldsymbol{e}_t$, such as money demand and conventional monetary policy shocks.[12] As in Jorda et al. (2015) and Ramey

[10] Notice that there is no need to include any contemporaneous variables $\boldsymbol{w}_t$ in Equation (26) on the right-hand side because of the presence of the contemporaneous values of the structural QE and non-QE shocks $\boldsymbol{e}_t$.

[11] As we do not have information on the signs of $\boldsymbol{\delta}$ and $\boldsymbol{a}_0$ we cannot predict whether the endogeneity bias affecting the estimate of α_h^{qe} is positive or negative.

[12] Notice that there is also a possibility of endogeneity of some of the determinants of the relative balance sheet $\sum_{m=1}^{M} \boldsymbol{w}_{t-1+m}$ in the second-stage regression in Equation (27); for example, $\boldsymbol{w}_t$ includes the contemporaneous relative balance sheet BS_t, see Equation (26). We address this possibility by estimating Equation (27) without controlling for $\sum_{m=1}^{M} \boldsymbol{w}_{t-1+m}$ in the baseline specification. We discuss in more detail the specification of the

and Zubairy (forthcoming), in order to address this endogeneity we adopt a local projection two-stage least squares approach using QE announcements as instruments for $\sum_{m=1}^{M} \Delta BS_{t+m}$ in Equation (27).[13] In particular, we assume that ECB and Federal Reserve QE announcements a_t^{ECB} and a_t^{Fed} are related to anticipated relative QE shocks according to:

$$\eta_{t+m|t} = \sigma_m + \mu_m^{\text{ECB}} a_t^{\text{ECB}} + \mu_m^{\text{Fed}} a_t^{Fed} + u_{t,m}, \quad m = 1, \ldots, M. \tag{29}$$

The intuition for Equation (29) is that a QE announcement in period t is followed by changes in the relative balance sheet m periods in the future. Summing Equation (29) over horizons m yields:

$$\begin{aligned} \sum_{m=1}^{M} \eta_{t+m|t} &= \left(\sum_{m=1}^{M} \sigma_m\right) + \left(\sum_{m=1}^{M} \mu_m\right) a_t^{\text{ECB}} + \left(\sum_{m=1}^{M} \mu_m\right) a_t^{\text{Fed}} + \left(\sum_{m=1}^{M} u_{t,m}\right) \\ &= \overline{\sigma} + \overline{\mu}^{\text{ECB}} a_t^{\text{ECB}} + \overline{\mu}^{\text{Fed}} a_t^{\text{Fed}} + \overline{u}_t. \end{aligned} \tag{30}$$

In turn, summing the relative balance sheet in Equation (26) over horizons $m = 1, 2, \ldots, M$ yields:

$$\begin{aligned} \sum_{m=1}^{M} \Delta BS_{t+m} &= M\delta_0 + \rho \sum_{m=1}^{M} \boldsymbol{w}_{t-1+m} + \sum_{m=1}^{M} \sum_{k=1}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \sum_{m=1}^{M} \boldsymbol{e}_{t+m} \\ &= M\delta_0 + \rho \sum_{m=1}^{M} \boldsymbol{w}_{t-1+m} + \sum_{m=1}^{M} \eta_{t+m|t} + \sum_{m=1}^{M} \sum_{\substack{k=1 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \sum_{m=1}^{M} \boldsymbol{e}_{t+m}, \end{aligned} \tag{31}$$

which shows that our variable of interest that is affected by endogeneity in Equation (27), $\sum_{m=1}^{M} \Delta BS_{t+m}$, is correlated with the sum of future anticipated QE shocks $\sum_{m=1}^{M} \eta_{t+m|t}$, which can be forecast by QE announcements in Equation (30). Against the background of Equations (27), (30) and (31), we thus consider a two-stage least squares regression approach in which the second-stage regression is given by Equation (27) and the first-stage regression by

$$\sum_{m=1}^{M} \Delta BS_{t+m} = \varpi + \theta^{\text{ECB}} a_t^{\text{ECB}} + \theta^{\text{Fed}} a_t^{\text{Fed}} + \omega_{t-1,h} + \sum_{m=1}^{M} \boldsymbol{\gamma}_m' \boldsymbol{w}_{t-1+m} + \xi_t. \tag{32}$$

Our identifying assumptions are that the instruments for the relative balance sheet variable $\sum_{m=1}^{M} \Delta BS_{t+m}$ in Equation (27) given by the QE announcements a_t^{ECB} and a_t^{Fed} in period t:

(i) are uncorrelated with the error term in the second-stage regression $\zeta_{t,h}$ defined in Equation

dependent and the explanatory variables in Section 3.

[13] The use of external instruments was originally introduced in the VAR context by Stock and Watson (2012) and Mertens and Ravn (2013), and has recently gained prominence through Gertler and Karadi (2015).

(28), i.e. with contemporaneous non-QE structural shocks, $\boldsymbol{e}_t$, as well as future QE and non-QE structural shocks $\nu_{t,h}$ and $\boldsymbol{e}_{t+m}$ (instrument validity)

(ii) predict changes in the relative balance sheet between periods t and $t+m$ in the future, i.e. $\theta^{\text{ECB}} \neq 0$ and/or $\theta^{\text{Fed}} \neq 0$ in Equation (32) (instrument relevance)

Notice that (ii) is satisfied already when $\mu_m^{\text{ECB}} \neq 0$ and/or $\mu_m^{\text{Fed}} \neq 0$ from Equation (29) for *some* horizon m. We test these assumptions by means of the Hansen J-test of over-identification and the Kleibergen and Paap (2006) test of under-identification. We also consider tests for weak instruments of Montiel Olea and Pflueger (2013) based on the effective F-statistic as implemented in Stata by Pflueger and Wang (2015).[14]

3 Empirical specification

3.1 Sample period

Since we are interested in the effects of QE measures introduced in the wake of the global financial crisis and its aftermath, our sample period spans January 2009 to October 2017. Our analysis is carried out using data sampled at the monthly frequency; we consider weekly data in robustness checks in Section 5. We transform the data for financial variables available at higher frequencies to monthly observations by calculating averages over daily or weekly data. The data on the US dollar-euro exchange rate as well as the size of the ECB's and the Federal Reserve's balance sheets are obtained from Haver Analytics.

3.2 Dependent variable and controls

We specify BS_t as the logarithm of the ratio of the ECB's and the Federal Reserve's nominal balance sheet in their respective currencies. The variable $\sum_{m=1}^{M} \Delta BS_{t+m}$ then boils down to the percentage point change of the relative balance sheet between periods $t+m$ and t, i.e. $BS_{t+m} - BS_t$. Notice that $BS_{t+m} - BS_t$ also represents the percentage points difference between

[14] Stock and Watson (2017) discuss an additional "lead/lag exogeneity" requirement for consistent estimation in the context of local projections with external instruments. In particular, *in general* instruments need to be uncorrelated with future and also *past* structural shocks. Applied to this paper this requires that QE announcements must be uncorrelated with past structural—such as demand and risk—shocks. To the extent that QE measures are a systematic response of central banks to adverse shocks, this requirement is unlikely to be satisfied. However, the derivation of our local projection regression equation from a structural equation for the exchange rate shows that in this particular context our estimation only requires that QE announcements are uncorrelated with contemporaneous and future structural shocks. We nevertheless address the issue of "lead/lag exogeneity" in more detail in Section 5, where—as suggested by Stock and Watson (2017)—we control for past structural shocks.

the nominal growth rates of the ECB's and the Federal Reserve's balance sheets between periods $t+m$ and t.

We proxy the variables in the vector $\omega_{t-1,h}$ that includes period $t-1$ values and period $t-1$ expectations of subsequent values of the fundamental determinants of the exchange rate by lagged values of the three-month money-market and policy rate differentials, CIP deviations, the VIX, as well as ECB and Federal Reserve QE announcements. For interest rates we consider three-month money market rates obtained from Haver Analytics. For the respective policy rates we use the Federal Funds target rate as well as the ECB deposit facility rate (DFR). We measure the CIP deviation by the three-month cross-currency basis obtained from Bloomberg, multiplied by minus one in order to account for the differences in the definition of the basis and the CIP deviation in this paper (see Section 2.1). As the term $\sum_{m=1}^{M} \boldsymbol{w}_{t-1+m}$ on the right-hand side of the second-stage regression in Equation (27) might be endogenous due to its correlation with non-QE shocks $\sum_{m=1}^{M} \boldsymbol{e}_{t+m}$, in our baseline specification we do not include it as control. We report results for regressions which include these controls in Section 5.

In order to more cleanly identify QE shocks and to distinguish them from conventional monetary policy shocks, we include the contemporaneous policy rate differential as a control in the second and first-stage regressions. This element of our identification strategy corresponds to the assumption of a Choleski ordering in a VAR in which the relative balance sheet would be ordered after those variables whose contemporaneous values appear in our first-stage regression. Intuitively, our identification assumption here is that QE shocks do not contemporaneously affect the policy rate differential. Notice that this is almost trivially true, as both the policy rate and the balance sheet are under the control of the central bank and due to the practice of monetary policy implementation: On the one hand, conventional monetary policy shocks on the policy rate may involve a contemporaneous change in the central bank balance sheet, as this is the rate that is charged on banks for borrowing reserves from the central bank; on the other hand, QE shocks in the form of central bank asset purchases can be implemented without contemporaneous changes in policy rates.

Finally, in order to decompose the response of the exchange rate to QE shocks as laid out in Equation (13), we also estimate the dynamic responses of the euro-dollar short-term money market rate differential as well as the CIP deviation. We do so by replacing the left-hand side variable in the second-stage regression in Equation (27) accordingly.

3.3 QE announcements

We specify the QE announcements a_t^{ECB} and a_t^{FED} as indicator variables which equal unity if the Federal Reserve or the ECB reveal some information about future asset purchases or credit easing programs. Tables 1 and 2 report the ECB and Federal Reserve QE announcements we consider.[15] The dates in question are assigned to their respective calendar month t.[16] We only consider QE announcements that had a tangible impact on central banks' balance sheets. For example, we do not include the announcements of the ECB's intention to do "whatever it takes to preserve the euro" in July 2012 and of the Outright Monetary Transactions programme in September 2012, because these announcements did not result in asset purchases by the time of writing. Furthermore, we do not include the ECB announcement of the Securities Market Programme in May 2010, because the associated asset purchases were sterilised and did therefore not increase the ECB's balance sheet. Following the same logic, we do not consider the Federal Reserve's announcements of its maturity extension programme "Operation twist", which resulted in an increase of the weighted average maturity of the central banks' asset holdings, but did not expand the balance sheet. If we included these QE announcements in our analysis, their power as instruments in the first-stage regression would necessarily be impaired.

Tables 1 and 2 also report information on the response of the Eurostoxx and S&P500 stock markets on the day of the ECB and Federal Reserve QE announcements, respectively. In most cases, stock market movements on the announcement days have been notable, i.e. greater than 0.5%, suggesting that the announcements had at least some surprise component. We discuss the relevance of the instances in which the stock market responses were negative in the robustness checks in Section 5.

An alternative to QE announcement dummies would be to consider surprises based on surveys or polls, which could also take into account differences in the size and scope of the QE measures. For a subset of the announcements survey data and polls on the size of the QE measures expected by professional forecasters are indeed available. However, these data are not available systematically. One reason for the lack of systematic availability of such polls is that the size of the measures in question was not known upon announcement in some cases; for example, in the case of various exceptional liquidity operations conducted by the ECB, the overall size of the measures ultimately depended on take-up by banks rather than being determined by the ECB. In addition, such survey data only capture expectations of selected professional forecasters, and hence might not necessarily overlap with expectations of the market as a whole. Nevertheless, we consider a robustness check in Section 5 in which we use the changes in equity prices on the day of the announcement to weigh unconventional monetary policy measures.

[15]The announcement dates of the QE measures of the Federal Reserve are taken from Rogers et al. (2014). Those for the ECB are taken from the ECB's website.

[16]The dummies also equal unity when there is more than one announcement in a given month, but this occurs only once in our dataset in the case of Federal Reserve announcements in October 2010.

4 Estimation results

4.1 First-stage regression: Predictive content of QE announcements

Table 3 reports the estimation results for the first-stage regression in Equation (32).[17] We report results for $M = 1, 2, \ldots, 5$ in Equation (24). The estimates indicate that ECB and Federal Reserve QE announcements in period t predict future changes in the relative balance sheet. Specifically, following an ECB QE announcement, its balance sheet expands statistically significantly relative to that of the Federal Reserve by 1.9 percentage points after one month, 3.7 percentage points after two months, and up to 8.9 percentage points after five months. To put these numbers in perspective, notice that a one percentage point expansion of the ECB's balance sheet relative to that of the Federal Reserve in September 2015 when the APP was announced for the first time amounted to an expansion by roughly 45 bil. euros.[18] Notice that this is slightly below the monthly asset purchases of 60 bil. euros under the ECB's APP program. In turn, following a Federal Reserve QE announcement, the Federal Reserve's balance sheet expands statistically significantly by 3.4% only after two months relative to that of the ECB, and by up to 9.5% after five months. Finally, the results reported in Table 3 document that the estimated models do not reject the null of instrument validity according to the Hansen J-test, and that they reject the null of under-identification according to the Kleibergen and Paap (2006) tests. Moreover, at least the specifications with $M > 2$ are associated with an effective F-statistic that is larger than the—at least 10% significance level—corresponding critical value, suggesting that the instruments in these cases are unlikely to be weak.[19] Notice also that—as we would expect given that it becomes more likely that $\mu_m^{\text{ECB}} \neq 0$ and/or $\mu_m^{\text{Fed}} \neq 0$ in Equation (29) holds for *some* horizon m as M increases—the effective F-statistics generally increase with M. We choose the specification with $M = 3$ as our baseline in the following.[20]

4.2 Second-stage regression: Dynamic effects of QE shocks

We now turn to the dynamic responses of the nominal bilateral US dollar-euro exchange rate, the relative balance sheet, and the fundamental determinants of the exchange rate in Equation

[17] Standard errors are robust to heteroskedasticity and serial correlation.

[18] In September 2015 the ECB's balance sheet stood at about 2 tn. euros, and that of the Federal Reserve at around 4.5 tn. USD. The relative balance sheet was thus $(2\,tn.\,\text{euro})/(4.5\,tn.\,\text{USD}) = 0.4444$. The implied balance sheet of the ECB in case of an expansion of the relative balance sheet by one percentage point is given by $(4.5\,tn.\,\text{USD}) \times 0.4544$.

[19] As suggested by Montiel Olea and Pflueger (2013) and as in Ramey and Zubairy (forthcoming) we consider critical values at the 5% and 10% significance level for the null hypothesis that the bias of the two-stage least squares estimator is greater than 10% of the "worst-case" benchmark.

[20] All impulse response estimates for the specifications with $M \neq 3$ can be found in the Online Appendix.

(13). All impulse response estimates are reported with asymptotic confidence bands at the 95% significance levels that are robust to heteroskedasticity and serial correlation.

4.2.1 Relative balance sheet response

The top left-hand side panel in Figure 2 shows the dynamic response of the relative balance sheet to the relative QE shock ε_t^{qe} in Equation (24). Specifically, the impulse response is obtained from a two-stage least squares estimation analogous to that for the exchange rate in Equation (27), but in which the dependent variable in the second stage is the relative balance sheet. The estimates suggest that in response to the relative QE shock, the ECB's balance sheet expands statistically significantly relative to that of the Federal Reserve for around ten months. The peak expansion of around 1.9 percentage points occurs after seven months. On the one hand, the gradual build-up of the relative balance sheet in response to the relative QE shock shown in Figure 2 is consistent with the fact that ECB and Federal Reserve QE measures were typically not one-off instances of asset purchases or liquidity injections, but were carried out repeatedly over time. On the other hand, the mean reversion in the response of the relative balance sheet might seem at odds with precisely this persistent nature of the QE measures of the ECB and the Federal Reserve. Yet, recall that the left-hand side panel of Figure 1 shows that the *relative* balance sheet has been mean reverting over the sample period we consider.

4.2.2 Policy-rate differential response

The top right-hand side panel in Figure 2 shows the dynamic response of the policy rate differential to the relative QE shock.[21] While the impact response is by assumption restricted to be zero, also the point estimates for the response after up to five months after the QE shock are very close to zero.[22] After six months the point estimates indicate a drop in the policy rate differential, which, however, becomes statistically significant only after twelve months. The policy rate differential falls by up to four basis points after 18 months. The lack of a statistically significant drop in the policy rate differential in the very short term suggests that we are not confounding the effects of a QE shock with those of a conventional monetary policy shock. Instead, the delayed drop in the policy rate differential suggests that QE measures were successful in signalling further monetary policy accommodation in the short to medium term. The finding

[21] The results are almost identical when we consider the ECB's main refinancing operations (MRO) rate rather than the DFR.

[22] We impose that the policy rate differential does not react to QE shocks on impact by including on the right-hand side in the local projection regression in Equation (27) the contemporaneous policy rate differential as control. As a consequence, for $h = 0$ the fit of the local projection regression is perfect, with a coefficient estimate of unity on the contemporaneous policy rate differential, and a coefficient estimate of zero on the instrumented relative balance sheet change.

of no fall in the policy rate differential in the short term is all the more noteworthy as the ECB lowered its policy rates several times during the sample period we consider; for example, the ECB's DFR (MRO) was lowered from 2% (2.5%) to -0.4% (0%) between January 2009 and March 2016, including four instances in which ECB QE measures were announced alongside policy rate changes.

4.2.3 US dollar-euro exchange rate response

The bottom panel in Figure 2 shows that the euro depreciates persistently and statistically significantly in response to the relative ECB QE shock. The depreciation bottoms at around 1.1% after nine months. Read in connection with the response of the relative balance sheet, the estimates suggest that a QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve by up to 1.9 percentage points depreciates the euro by up to 1.1%. Figure 3 presents the exchange rate impulse responses for all values of M that we consider in order to document that the estimates of the response of the main variable of interest do not depend on the choice of this parameter. Each panel in Figure 3 also reports confidence bands that are robust to possible weak instruments.[23] Quantitatively, our results imply that the APP program, which expanded the ECB's balance sheet by 35 percentage points relative to that of the Federal Reserve between September 2014 when the APP was announced for the first time and the end of 2016, depreciated the euro vis-à-vis the US dollar by about 20% ($= 35pp/1.9pp \times 1.1\%$). This is a substantial effect when compared to the overall depreciation of the euro vis-à-vis the US dollar by roughly 20% over the same time period. Of course, one has to bear in mind that in the data the exchange rate is also affected by other shocks, and that we do not carry out an exhaustive historical decomposition. For example, the euro started to appreciate notably vis-à-vis the US dollar from mid-2017 on the back of a strengthening euro area economy, despite the continuation of the ECB's asset purchases under the APP program.

4.2.4 Decomposition of the exchange rate response

We now consider the channels through which QE shocks transmit to the exchange rate by investigating the responses of its fundamental determinants according to Equation (13), i.e. the interest rate differential, the CIP deviation and currency risk premia.

[23] The confidence bands are based on the numerical inversion of the p-values of the conditional likelihood ratio test as implemented in Stata by Finlay and Magnusson (2009). The null hypothesis of this test is $H_0: \alpha_h^{qe} = 0$. The conditional likelihood ratio statistic is robust to weak instruments in the sense that identification of the coefficients is not assumed under the null. This is in contrast to the traditional instrumental variables estimation methods, where the validity of tests on estimated coefficients requires the assumption that they are identified. Due to the numerical nature of the construction of the confidence intervals, these can be disjoint and open-ended. For example, open-ended confidence intervals commonly arise when the grid does not extend far enough to capture the point where the rejection probability crosses the level of significance.

Interest rate differential The left-hand side panel in Figure 4 depicts the estimated response of the three-month euro-dollar money market rate differential. The estimates suggests that euro area money market rates decline statistically significantly relative to those in the US in response to a relative ECB QE shock. The short-term money market rate differential falls statistically significantly after three months, and bottoms at around five basis points after twelve months. Overall, the response of the short-term money market rate differential is–at least based on the point estimates—consistent with that of the policy rate differential, in the sense that the former at every point in time reflects expectations of the latter over the subsequent three months.

CIP deviation Recall the definition of the CIP deviation in Equation (6)

$$\lambda_t = r_t^{€} - \left(r_t^{\$} - f_{t,t+1} + s_t \right), \tag{33}$$

and also that this definition coincides with that of the cross-currency basis, except for having the opposite sign (Du et al., 2017). Intuitively, with our definition a positive value of the CIP deviation amounts to a euro cash rate that is larger than the synthetic euro rate (or a larger synthetic dollar rate than its cash counterpart); alternatively, for a given interest rate differential, one can think of a positive value of the CIP deviation as one euro having a lower price in terms of US dollars in the forward than in the spot market than what CIP would imply. The right-hand side panel in Figure 4 presents the estimated response of the CIP deviation to the relative ECB QE shock. The estimates suggest that the CIP deviation rises statistically significantly by up to around one basis point for three months in response to the relative QE shock. Our results thus imply that relative ECB QE shocks have contributed to the widening of the cross-currency basis over the sample period we consider, which is consistent with the findings of Sushko et al. (2016) as well as Du et al. (2017). The rationale for relative ECB QE shocks increasing the CIP deviation—or rendering more negative the cross-currency basis—typically alluded to in this context relates to an asymmetry between the demand and supply for foreign exchange swap contracts for high and low-yield currencies. In particular, lower funding costs in the euro area caused by ECB QE shocks attract foreign borrowers, who desire to hedge their euro exposure and thereby increase the demand for swap contracts. Against the background of a limited supply of such contracts, foreign borrowers accept a lower price for one euro in terms of US dollars in the forward market—i.e. a lower value of $f_{t,t+1}$—than what CIP would imply. In terms of the definition of the CIP deviation reflecting differential tightness of borrowing constraints in cash and synthetic dollar markets discussed in Section 2, the estimated increase in the CIP deviation implies that from a US investor's perspective a relative ECB QE shock eases borrowing constraints in the synthetic dollar market relative to those in the cash market.

Contributions of individual fundamentals to overall exchange rate response Figure 5 presents the decomposition of the exchange rate response to the relative ECB QE shock into the contributions accounted for by the responses of the short-term money market rate differential, the CIP deviation, and the expected future exchange rate;[24] the contribution of currency risk premia is obtained as a residual, taking as given the estimates of the responses of the exchange rate, the interest rate differential and the CIP deviation. The results suggest that falling current and expected future interest rate differentials and a remaining expected depreciation after 18 months contribute to the depreciation of the euro relative to the US dollar on impact in response to the relative QE shock. On impact, however, the increase in currency risk premia almost completely offsets this. The contribution of the CIP deviation is marginal, which is due to the statistically not significant fall in the point estimates of the response of the CIP deviation at longer horizons, which in the cumulation $\sum_{j=0}^{T-1} E_t \lambda_{t+j}$ offsets the positive response in the short term (see Figure 4). All four channels—interest rate differentials, CIP deviations, currency risk premia and the future expected exchange rate—contribute to a similar extent to the overall exchange rate response, at least at some horizon. That risk premia play an important role in the dynamics of exchange rates echoes the findings of the classic study of Engel and West (2010), who find that a large share of the variation in the dollar exchange rate are attributable to a residual risk premium component.

Other financial market variables Even though they are not directly related to understanding the exchange rate response, it is still insightful to explore the effects of QE shocks on other financial variables. We focus on the responses of euro area variables which are not relative in nature, and correspondingly consider only the ECB balance sheet as well as ECB QE announcements. Figure 6 presents the responses of sovereign bond yield differentials at the two and ten-year maturities, the expectations and the term-premium component of the ten-year rate, as well as euro area equity prices;[25] we again consider the specification with $M = 3$. The euro area two-year sovereign bond yield drops statistically significantly and persistently by up to three basis points in response to the ECB QE shock. The estimates of the response of the ten-year sovereign bond yield are somewhat larger, less precisely estimated and less persistent. In particular, the ten-year yield drops by up to six basis points after six months, which is economically significant. For instance, applying the same logic as for the exchange rate above, these results imply that the ECB's APP program, which expanded the ECB's balance sheet by 35 percentage points relative to that of the Federal Reserve between September 2014 and the end of 2016 led

[24]The decomposition is based on the point estimates and does not take into account estimation uncertainty. In the Online Appendix we show that the results are very similar if we consider only the statistically significant estimates.

[25]We consider two and ten-year sovereign bond yields obtained from Haver Analytics. We use German Bund yields as measures of euro area sovereign yields. The expectations and the term-premium component are taken from the ECB Statistical Data Warehouse and are calculated from a standard Nelson-Siegel term-structure model.

to a drop of the ten-year yield by about one percentage point ($= 35pp/1.9pp \times 0.06pp$). This is a substantial effect when compared to the overall decline in ten-year sovereign yields of about one percentage point over the same time period. Interestingly, the decline in the ten-year sovereign bond yield can largely be traced back to a commensurate drop in the term-premium component. Finally, equity prices rise—somewhat surprisingly—with a substantial delay after ten months by up to 1.1%. This effect is again economically significant, as it implies that the ECB's APP program raised equity prices cumulatively by about 20% between September 2015 and the end of 2016 ($= 35pp/1.9pp \times 1.1\%$).

5 Robustness

Consistent with the presentation of the results for the baseline specification, for all robustness checks we report the first-stage regression results for $M = 1, 2, \ldots, 5$ in Equation (24), and impulse response estimates for $M = 3$.

5.1 Regression with control variables $\sum_{m=1}^{M} \boldsymbol{w}_{t+m-1}$

In our baseline we exclude the determinants of the relative balance sheet $\sum_{m=1}^{M} \boldsymbol{w}_{t-1+m}$ from the control variables of the first and second-stage regressions, as it might be endogenous due to its correlation with non-QE shocks $\sum_{m=1}^{M} \boldsymbol{e}_{t+m}$ in the second-stage regression in Equation (27). However, in the absence of endogeneity including these controls would be preferable, as the fit would be improved and standard errors would be smaller. Table 4 and Figure 9 present the results for the specification in which we include $\boldsymbol{w}_{t-1+m}$, $m = 1, 2, \ldots, M$, in the first and second-stage regressions as controls; in $\boldsymbol{w}_t$ we include the relative balance sheet only. The results are very similar to those from our baseline, even though the coefficient estimates are somewhat less precise and the effective F-statistic is somewhat lower.

5.2 Allowing for contemporaneous effects of QE shocks

One could argue that QE shocks which materialise in period t do not only elicit central bank asset purchases in the future, but also contemporaneously. Formally, instead of Equation (24) one would then have to specify

$$\varepsilon_t^{qe} = \sum_{m=0}^{M} \eta_{t+m|t}, \tag{34}$$

which now includes $\eta_{t|t}$ on the right-hand side. If Equation (34) is true rather than Equation (24), then our instruments in the baseline might be invalid. Specifically, notice that in this case, substituting only $\eta_{t+m|t}$ for $m > 0$ in Equation (25)—as we do in Section 2.4—implies that $\eta_{t|t}$ appears in the error term $\zeta_{t,h}$ of the second-stage regression in Equation (27). If QE announcements in period t contain information about contemporaneous central bank asset purchases, i.e. $Cov(a_t^i, \eta_{t|t}) \neq 0$, our instruments would be correlated with the error term $\zeta_{t,h}$ of the second-stage regression. While the results of the Hansen J-test do not reject the null of instrument validity, it is nevertheless worthwhile to explore the robustness of our results along this dimension.

We address the possibility that the instruments might be invalid by changing the specification of the variable of interest. In particular, in case Equation (34) is true rather than Equation (24) we can substitute $\eta_{t|t}$ in Equation (25) using

$$\eta_{t|t} = \Delta BS_t - \left(\delta_0 + \boldsymbol{\rho}' \boldsymbol{w}_{t-1} + \sum_{k=1}^{M} \eta_{t|t-k} + \boldsymbol{\delta}' \boldsymbol{e}_t \right),$$

based on a generalisation of Equation (26). The local projection equation for the exchange rate is then given by

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} \Delta BS_{t+m} \right) + \omega_{t-1,h} - \alpha_h^{qe} \rho \sum_{m=0}^{M} \boldsymbol{w}_{t-1+m} + \widetilde{\delta}_0 + \zeta_{t,h}, \tag{35}$$

where

$$\zeta_{t,h} \equiv -\alpha_h^{qe} \boldsymbol{\delta}' \sum_{m=0}^{M} \boldsymbol{e}_{t+m} - \alpha_h^{qe} \sum_{m=0}^{M} \sum_{\substack{k=1 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{a}_0' \boldsymbol{e}_t + \nu_{t,h}, \tag{36}$$

which boils down to considering $BS_{t+m} - BS_{t-1}$ rather than $BS_{t+m} - BS_t$ as variable of interest. The results reported in Table 5 and Figure 10 are very similar to those from our baseline. If anything, the coefficients in the first-stage regression are estimated more precisely and the effective F-statistic is noticeably higher compared to the baseline.

5.3 QE announcements as systematic response to economic conditions

Another possible concern is that ECB and Federal Reserve QE announcements are not valid instruments because they are responses by the central bank to past demand shocks. In this case, our impulse response estimates would actually reflect the effects of the demand shock. Formally, QE announcements being a systematic response to economic conditions would violate the "lead/lag exogeneity" requirement for consistent estimation of local projections with external instruments (see Stock and Watson, 2017). However, the derivation of our local projection regression equation from a structural equation for the exchange rate shows that in the particular context of this paper QE announcements need only be uncorrelated with contemporaneous and future structural shocks. We nevertheless address the issue of possible failure of "lead/lag exogeneity" of the instruments by including the shocks to which the QE announcements might be responses to as controls in the second-stage regression (Jorda et al., 2015; Stock and Watson, 2017). Table 6 and Figure 11 document that the results are very similar to those from our baseline if we add three lags of the CitiGroup Macroeconomic Surprise indices as additional controls.[26] Again, if anything, the effective F-statistic is noticeably higher compared to the baseline.

5.4 Heterogeneity of QE measures and separating monetary policy from information shocks

Another possible concern with our approach is that the economic significance of the announcements might not be identical across QE measures. For example, some measures are bigger in magnitude than others, and some measures target specific asset classes. Moreover, conditional on the extent to which they were expected the QE measures underlying the announcements might still not elicit the same market responses even if they have the same size and scope; Tables 1 and 2 document that the market response measured by the change in equity prices on the same day was indeed different across announcements. And finally, it could also be that rather than being perceived as expansionary monetary policy shocks, some QE announcements might have been perceived by market participants as a revelation of private information by the central bank pointing to negative demand or financial shocks markets were not aware of (see Nakamura and Steinsson, 2013; Campbell et al., 2017); again, Tables 1 and 2 document that the stock market responses to QE announcements were indeed negative in some instances.

In order to address this concern, we borrow from the literature on the high-frequency identification of QE shocks (see, for example, Rogers et al., 2014; Jarocinski and Karadi, 2017). Specifically, rather than Equation (29) we assume the following relation between unobserved QE shocks and announcements:

$$\eta_{t+m|t} = \sigma_m + \mu_m^{\text{ECB}} a_t^{\text{ECB}} \cdot \Delta e_t^{€} \cdot I(\Delta e_t^{€} > 0) + \mu_m^{\text{Fed}} a_t^{\text{Fed}} \cdot \Delta e_t^{\$} \cdot I(\Delta e_t^{\$} > 0) + u_{t,m}, \qquad (37)$$

where $\Delta e_t^{€}$ and $\Delta e_t^{\$}$ represent the changes in euro area and US equity prices on the day of QE announcements, respectively, and $I(\Delta e_t^{€} > 0)$ and $I(\Delta e_t^{\$} > 0)$ are indicator variables which equal unity when the equity price changes are positive and zero otherwise. Equation (37) implies that we weight QE announcements a_t^j by the domestic equity price response on the day of the announcement, and that we consider only those QE announcements which were followed by

[26] The results are very similar for different lag orders and if we consider industrial production or inflation instead of the CitiGroup Macroeconomic Surprise indices.

a positive equity price response. Doing so allows us to select those QE announcements for which the QE shock component dominated any possible informational shock component that would reflect the revelation of the central bank outlook differing from that of the market. The results for the first-stage regression of this specification are reported in Table 7, and the impulse responses in Figure 12. The results are overall similar to those from our baseline. However, the effective F-statistic is noticeably lower compared to the baseline.

5.5 Identifying QE shocks narratively

The power of the QE announcement dummies we consider as instruments is reduced by the fact they were not all followed by an expansion of the central banks' balance sheets. For example, some of the QE announcements we consider were pre-announcements, such as the ECB's CSPP announcement in March 2016. The power of our instruments would be improved if we could consider only those QE announcements which were indeed followed by an expansion of central banks' balance sheets. Against this background, notice that the coefficient estimates of the QE announcement dummies in the first-stage regression are given by the average of the residuals of the first-stage regression in the months in which the ECB and the Federal Reserve made QE announcements estimated *without* the corresponding dummies. In particular, the residuals of the first-stage regression estimated without the QE announcement dummies are positive (negative) in the months in which ECB (Federal Reserve) QE announcements were made and which were followed by expansions in the respective balance sheets. Inspecting the first-stage residuals from a regression without the QE announcement dummies shows that for the ECB the residuals are actually negative in four cases; for the Federal Reserve, the residuals are all negative except for one case.

In order to improve the power of our instruments by identifying QE shocks which actually did increase the central banks' balance sheets, we pursue a "narrative approach". In particular, we only consider those ECB (Federal Reserve) QE announcements which are associated with positive (negative) residuals in the first-stage regression estimated without the corresponding dummies. The results for the first-stage regression are reported in Table 8 and the impulse responses in Figure 13. Not surprisingly, the coefficient estimates of the ECB and Federal Reserve QE announcement dummies have the expected signs and are estimated more precisely, and the effective F-statistic is also noticeably higher than in the baseline. The impulse response estimates are very similar compared to those from the baseline.

5.6 Weekly data

In our baseline we do not use weekly data even if this would allow us to more accurately assign QE announcements to the respective periods. The reason for considering monthly rather than weekly data is that weekly central bank balance sheet data are considerably more noisy than the monthly data. Tables 10 and 11 report the first-stage regression results for the specification with weekly data. In particular, Table 10 reports the results for our baseline regression specification, and Table 11 for the robustness checks discussed above. Figures 15 and 16 show the corresponding impulse response estimates. The results are once again very similar to those from our baseline, with the exception that the response of the CIP deviation is noticeably more persistent and somewhat less precisely estimated.

6 Concluding remarks

The exchange rate has been at the center stage of the discussion about the effectiveness, transmission channels and the spillovers from QE. Surprisingly, however, little research exists which is concerned with the estimation of the effects of QE on the exchange rate at frequencies and horizons that are relevant for policymakers. This paper addresses this gap in the literature. In particular, we estimate the effects of QE measures by the ECB and the Federal Reserve on the US dollar-euro exchange rate at frequencies and horizons relevant for policymakers. We do so by using two-stage least squares regressions of theoretically consistent local projections for the exchange rate, in which QE announcements serve as instruments for changes in central banks' relative balance sheet. Deriving the local projection regression equation from a structural equation for the exchange rate disciplines the empirical specification we bring to the data, for example by pointing to possible sources of endogeneity, guiding the choice of control variables and their timing. We also pay great attention to model specification tests, including instrument validity and power. We find that QE measures have large and persistent effects on the exchange rate, and that they materialise in particular through a change in interest rate differentials that reflect expectations of the future monetary policy stance.

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A Tables

Table 1: ECB announcements of unconventional monetary policy measures

Date	Event	Stock market response
07/05/2009	12-month SLTROs and other measures	-0.99%
04/08/2011	SLTROs and other measures	0.39%
06/10/2011	12/13-month SLTROs	2.74%
08/12/2011	36-month VLTROs and other measures	-2.09%
05/06/2014	Targeted longer term refinancing operations (TLTROs)	0.62%
04/09/2014	Announcement of ABSPP and CBPP3	0.73%
22/01/2015	Expanded Asset purchase programme (APP)	1.44%
05/03/2015	Implementation details of APP	0.65%
03/09/2015	Increase of PSPP's issue share limit	1.40%
10/03/2016	CSPP announcement	-0.98%
21/04/2016	CSPP starting date announcement and details	-0.30%
02/06/2016	CSPP Implementation details	0.07%
08/12/2016	Extension of APP	0.78%
26/10/2017	Extension of APP	0.75%

Note: The stock market response is the one-day change of the Eurostoxx 300 on the day of the announcements.

Table 2: Fed announcements of unconventional monetary policy measures

Date	Event	Stock market response
28/01/2009	Fed stands ready to expand QE and buy Treasuries	1.62%
18/03/2009	LSAPs expanded	0.08%
27/08/2010	Bernanke suggest role for additional QE	1.04%
12/10/2010	FOMC members 'sense' 'additional accommodation appropriate'	-1.07%
15/10/2010	Bernanke reiterates Fed stands ready to further ease policy	-0.54%
03/11/2010	QE2 announced: Fed will purchase $600 bn in Treasuries	0.00%
22/08/2012	FOMC members 'judge additional accommodation likely warranted'	-0.60%
13/09/2012	QE3 announced: Fed will purchase $40 bn of MBS per month	0.67%
12/12/2012	QE3 expanded	0.42%

Note: The stock market response is the one-day change of the S&P 500 on the day of the announcements.

Table 3: First-stage regression results: Baseline

	(1) $BS_{t+1} - BS_t$	(2) $BS_{t+2} - BS_t$	(3) $BS_{t+3} - BS_t$	(4) $BS_{t+4} - BS_t$	(5) $BS_{t+5} - BS_t$
ECB QE announcement	0.019***	0.037***	0.069***	0.079***	0.089***
	(2.95)	(3.31)	(5.50)	(4.86)	(4.69)
Fed QE announcement	-0.004	-0.034*	-0.046*	-0.053*	-0.095***
	(-0.41)	(-1.73)	(-1.68)	(-1.74)	(-3.51)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.16	0.59	0.30	0.28	0.46
Kleibergen-Paap-Test (p-value)	0.03	0.01	0.00	0.00	0.00
F-Stat (1st-stage)	4.63	8.12	21.79	16.52	22.29
Effective F-statistic	4.06	6.67	11.93	11.43	19.21
5% crit. value	6.27	8.74	14.01	12.09	7.34
10% crit. value	5.04	7.18	11.80	10.15	5.98
R-squared	0.41	0.52	0.54	0.56	0.59

t statistics in parentheses
Standard errors robust to heteroskedasticity and serial correlation
$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 4: First-stage regression results: With controls $\boldsymbol{w}_{t-1+m}$, $m = 1, 2, \ldots, M$

	(1) $BS_{t+1} - BS_t$	(2) $BS_{t+2} - BS_t$	(3) $BS_{t+3} - BS_t$	(4) $BS_{t+4} - BS_t$	(5) $BS_{t+5} - BS_t$
ECB QE announcement	0.014**	0.031**	0.062***	0.076***	0.088***
	(2.05)	(2.41)	(4.46)	(4.26)	(4.20)
Fed QE announcement	0.001	-0.029^{+}	-0.040^{+}	-0.050^{+}	-0.094***
	(0.05)	(-1.51)	(-1.54)	(-1.64)	(-3.41)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.13	0.61	0.31	0.29	0.49
Kleibergen-Paap-Test (p-value)	0.13	0.05	0.00	0.00	0.00
F-Stat (1st-stage)	2.11	4.16	14.27	12.23	16.77
Effective F-statistic	1.79	3.93	8.53	9.11	15.72
5% crit. value	7.13	6.34	12.15	10.45	6.06
10% crit. value	5.78	5.11	10.15	8.71	4.87
R-squared	0.42	0.53	0.55	0.56	0.59

t statistics in parentheses
Standard errors robust to heteroskedasticity and serial correlation
$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: First-stage regression results: Balance sheet variable given by $BS_{t+M} - BS_{t-1}$

	(1) $BS_{t+1} - BS_{t-1}$	(2) $BS_{t+2} - BS_{t-1}$	(3) $BS_{t+3} - BS_{t-1}$	(4) $BS_{t+4} - BS_{t-1}$	(5) $BS_{t+5} - BS_{t-1}$
ECB QE announcement	0.036***	0.053***	0.085***	0.096***	0.106***
	(4.45)	(4.46)	(5.62)	(5.13)	(4.73)
Fed QE announcement	-0.018	-0.048**	-0.060**	-0.067**	-0.109***
	(-0.95)	(-2.03)	(-2.17)	(-2.24)	(-3.74)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.19	0.47	0.24	0.23	0.39
Kleibergen-Paap-Test (p-value)	0.00	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	10.58	13.42	23.41	20.03	22.40
Effective F-statistic	6.03	10.27	16.30	15.73	20.67
5% crit. value	13.80	10.70	10.72	9.28	5.82
10% crit. value	11.60	8.88	8.92	7.68	4.65
R-squared	0.51	0.59	0.61	0.61	0.62

t statistics in parentheses
Standard errors robust to heteroskedasticity and serial correlation
$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6: First-stage regression results: Controlling for lagged macro shocks

	(1) $BS_{t+1} - BS_{t}$	(2) $BS_{t+2} - BS_{t}$	(3) $BS_{t+3} - BS_{t}$	(4) $BS_{t+4} - BS_{t}$	(5) $BS_{t+5} - BS_{t}$
ECB QE announcement	0.021***	0.039***	0.073***	0.083***	0.093***
	(2.85)	(3.23)	(4.82)	(4.52)	(4.57)
Fed QE announcement	-0.004	-0.033*	-0.044*	-0.053*	-0.098***
	(-0.35)	(-1.68)	(-1.70)	(-1.77)	(-3.47)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.12	0.58	0.26	0.28	0.60
Kleibergen-Paap-Test (p-value)	0.04	0.01	0.00	0.00	0.00
F-Stat (1st-stage)	4.26	7.36	16.11	13.98	20.84
Effective F-statistic	4.38	6.82	12.33	11.53	19.06
5% crit. value	4.97	6.71	9.18	9.10	7.32
10% crit. value	3.93	5.41	7.56	7.53	5.99
R-squared	0.42	0.54	0.58	0.60	0.64

t statistics in parentheses
Standard errors robust to heteroskedasticity and serial correlation
$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 7: First-stage regression results: QE announcements weighted by stock market surprise

	(1) $BS_{t+1} - BS_t$	(2) $BS_{t+2} - BS_t$	(3) $BS_{t+3} - BS_t$	(4) $BS_{t+4} - BS_t$	(5) $BS_{t+5} - BS_t$
ECB QE announcement	0.542	1.112*	2.775**	3.607*	5.709***
	(1.07)	(1.68)	(2.39)	(1.96)	(3.63)
Fed QE announcement	-0.361	-2.358**	-2.807*	-2.157+	-3.838*
	(-0.39)	(-2.06)	(-1.98)	(-1.43)	(-1.90)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.90	0.39	0.96	0.51	0.49
Kleibergen-Paap-Test (p-value)	0.40	0.06	0.02	0.02	0.02
F-Stat (1st-stage)	0.72	4.63	6.42	3.55	10.03
Effective F-statistic	0.52	4.04	5.40	3.59	9.12
5% crit. value	12.88	13.31	14.41	13.90	10.16
10% crit. value	10.88	11.27	12.41	11.75	8.55
R-squared	0.34	0.45	0.46	0.47	0.47

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8: First-stage regression results: Narrative approach

	(1) $BS_{t+1} - BS_t$	(2) $BS_{t+2} - BS_t$	(3) $BS_{t+3} - BS_t$	(4) $BS_{t+4} - BS_t$	(5) $BS_{t+5} - BS_t$
ECB QE announcement	0.022***	0.044***	0.067***	0.080***	0.099***
	(3.56)	(3.77)	(5.26)	(4.72)	(5.64)
Fed QE announcement	-0.019*	-0.060***	-0.071**	-0.079**	-0.094***
	(-1.79)	(-2.88)	(-2.46)	(-2.50)	(-3.61)
Observations	107	106	105	104	103
Hansen-J (p-value)	0.23	0.63	0.41	0.34	0.52
Kleibergen-Paap-Test (p-value)	0.01	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	9.00	14.17	24.91	19.23	29.69
Effective F-statistic	8.32	12.75	15.59	15.17	23.75
5% crit. value	5.24	7.47	13.38	11.12	8.44
10% crit. value	4.15	6.07	11.27	9.34	6.93
R-squared	0.42	0.54	0.55	0.54	0.61

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 9: First-stage regression results: Excl. APP announcements

	(1) $BS_{t+1} - BS_t$	(2) $BS_{t+2} - BS_t$	(3) $BS_{t+3} - BS_t$	(4) $BS_{t+4} - BS_t$	(5) $BS_{t+5} - BS_t$
ECB QE announcement	0.018*	0.047**	0.077***	0.072***	0.084**
	(1.78)	(2.61)	(4.29)	(2.65)	(2.59)
Fed QE announcement	-0.005	-0.037*	-0.055*	-0.065**	-0.109***
	(-0.48)	(-1.87)	(-1.97)	(-2.10)	(-3.95)
Observations	109	109	109	109	109
Hansen-J (p-value)	0.07	0.15	0.11	0.13	0.14
Kleibergen-Paap-Test (p-value)	0.23	0.04	0.01	0.02	0.01
F-Stat (1st-stage)	1.85	6.10	14.87	7.31	13.51
Effective F-statistic	1.70	5.43	8.80	6.09	11.55
5% crit. value	5.79	8.01	13.72	10.03	7.28
10% crit. value	4.63	6.58	11.54	8.36	5.91
R-squared	0.41	0.52	0.51	0.51	0.55

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 10: First-stage regression results: Weekly data

	(1) $BS_{t+4} - BS_t$	(2) $BS_{t+8} - BS_t$	(3) $BS_{t+12} - BS_t$	(4) $BS_{t+16} - BS_t$	(5) $BS_{t+20} - BS_t$
ECB QE announcement	0.012*	0.027**	0.053***	0.063***	0.067***
	(1.90)	(2.40)	(4.13)	(4.31)	(3.96)
Fed QE announcement	-0.007	-0.026+	-0.035+	-0.044+	-0.079***
	(-0.96)	(-1.62)	(-1.63)	(-1.64)	(-3.06)
Observations	464	460	456	452	448
Hansen-J (p-value)	0.12	0.35	0.13	0.15	0.32
Kleibergen-Paap-Test (p-value)	0.12	0.04	0.01	0.01	0.00
F-Stat (1st-stage)	2.40	4.29	10.16	10.90	13.00
Effective F-statistic	2.56	4.18	8.26	8.29	12.29
5% crit. value	7.78	3.99	11.36	14.29	11.98
10% crit. value	6.34	3.10	9.55	12.19	10.19
R-squared	0.29	0.37	0.43	0.43	0.44

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 11: First-stage regression results: Weekly data robustness

	(1) control	(2) $BS_{t+12} - BS_{t-1}$	(3) LIP	(4) Weighted	(5) Narrative
ECB QE announcement	0.056***	0.053***	0.074***	2.690*	0.083***
	(3.08)	(4.09)	(4.10)	(1.67)	(5.57)
Fed QE announcement	-0.070***	-0.034+	-0.075**	-5.086**	-0.111***
	(-2.79)	(-1.46)	(-2.47)	(-2.43)	(-5.70)
Observations	448	456	448	448	448
Hansen-J (p-value)	0.41	0.12	0.24	0.91	0.82
Kleibergen-Paap-Test (p-value)	0.01	0.01	0.00	0.04	0.00
F-Stat (1st-stage)	8.57	9.67	12.24	4.38	33.29
Effective F-statistic	8.58	7.47	10.66	4.22	32.11
5% crit. value	11.31	11.71	11.92	13.71	12.97
10% crit. value	9.64	9.84	10.07	11.83	11.17
R-squared	0.45	0.45	0.47	0.42	0.45

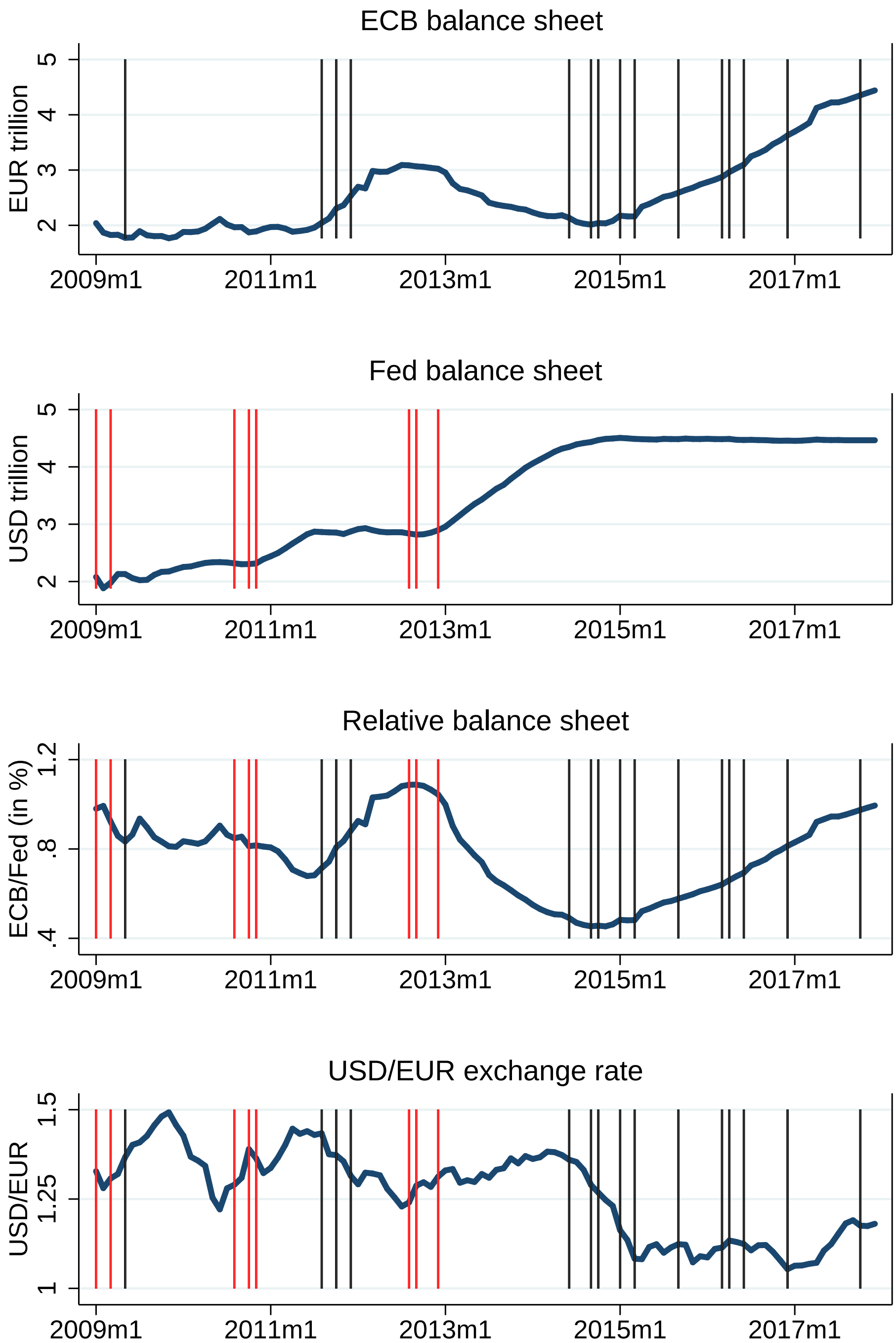
t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

B Figures

Figure 1: Balance sheet movements and QE announcements



Notes: The upper two panels of the figure show the evolution of the ECB's (top panel) and the Federal Reserve's (second from top panel) balance sheets. The second from the bottom panel shows the relative balance sheet (ECB/Fed). The bottom panel plots the USD/EUR exchange rate. Across all charts, the black (red) vertical lines indicate the dates of QE announcements by the ECB (Federal Reserve).

Figure 2: Impulse responses of the relative balance sheet, policy rate differential and exchange rate responses

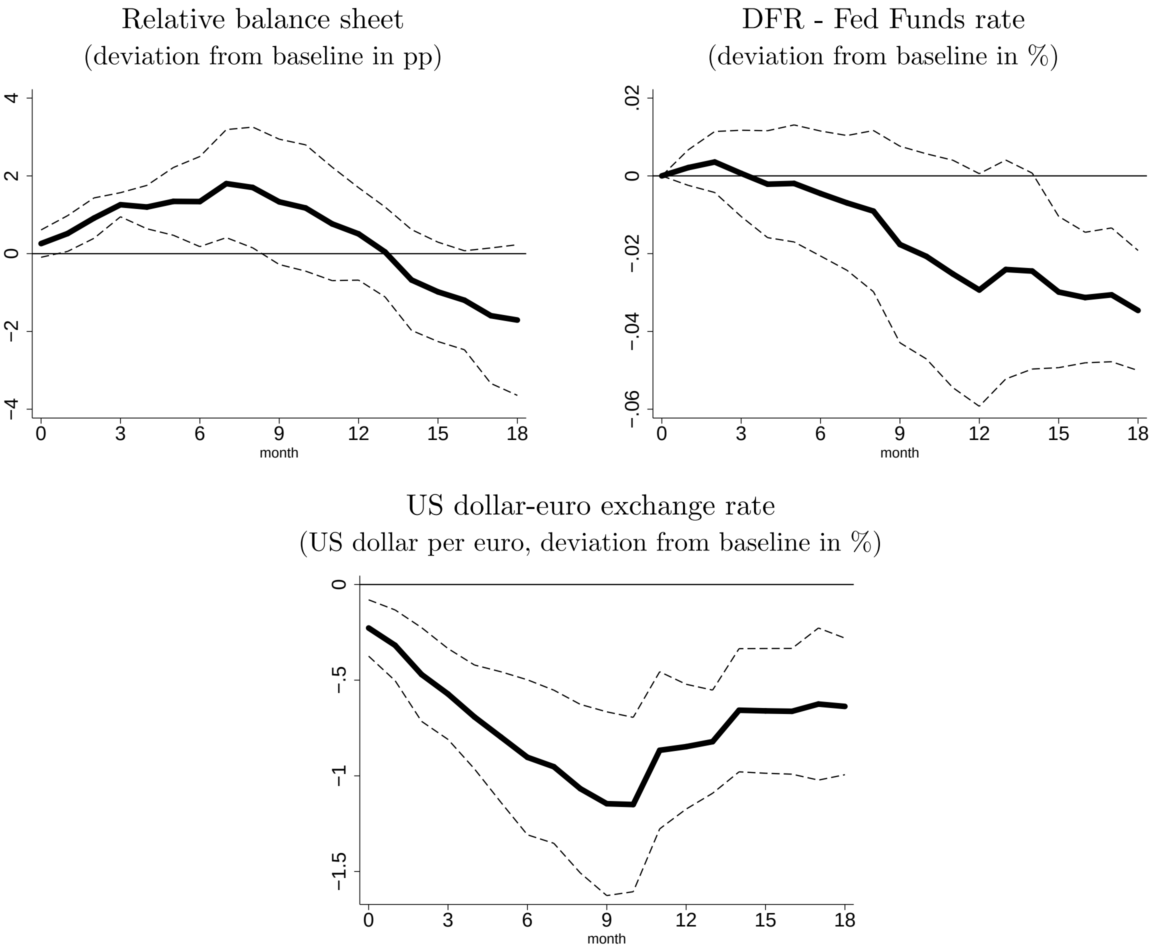


Figure 3: Exchange rate responses for $M = 1, 2, 3, 4, 5$

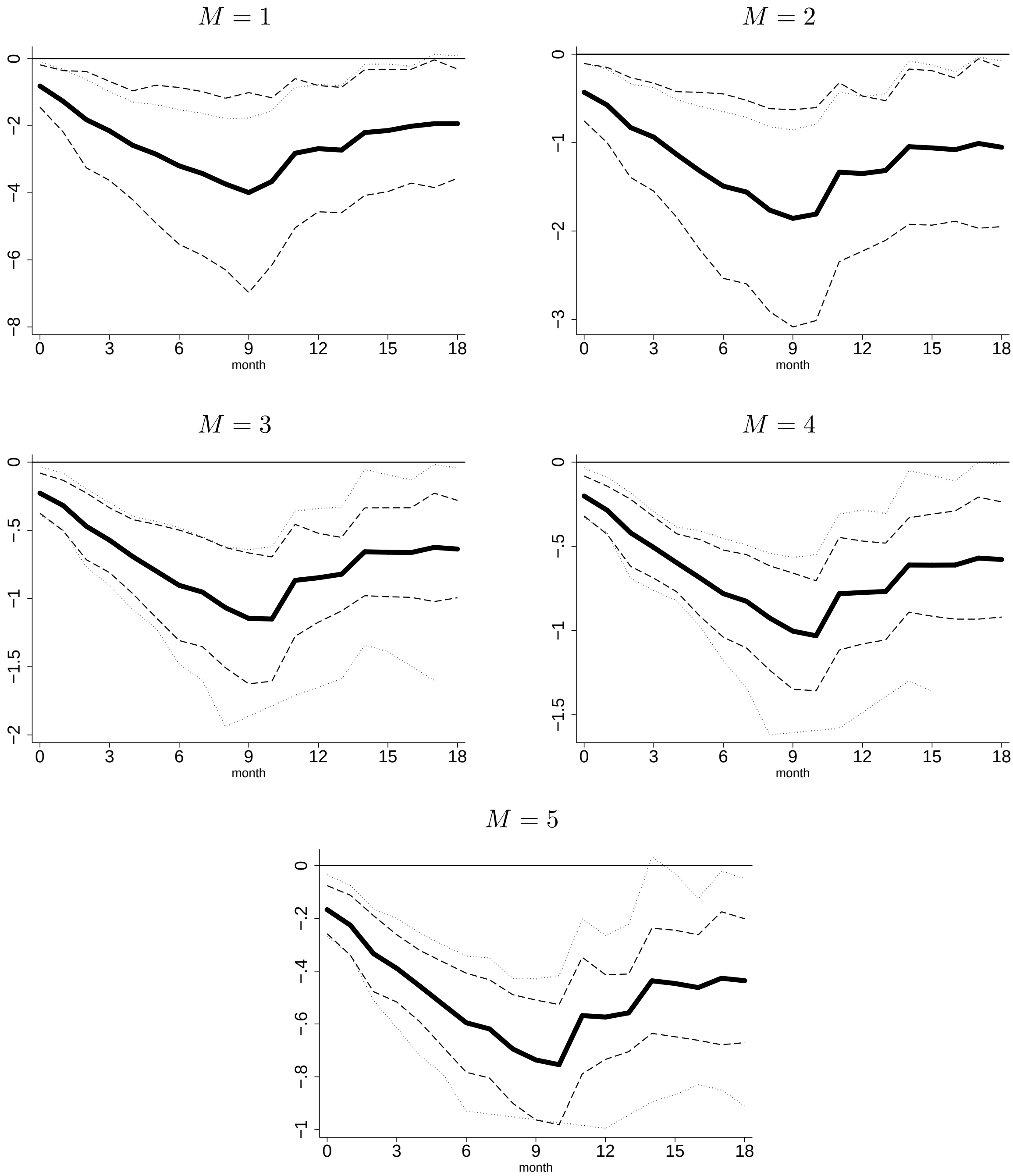


Figure 4: Impulse responses of the three-month money market rate differential and CIP deviation

Three-month money market rate differential $(r^{€,3m} - r^{\$,3m})$ (deviation from baseline in %-age points)

CIP deviation $(\lambda_t = f^{3m}_{t,t+1} - s_t + r^{€,3m}_t - r^{\$,3m}_t)$ (deviation from baseline in %-age points)

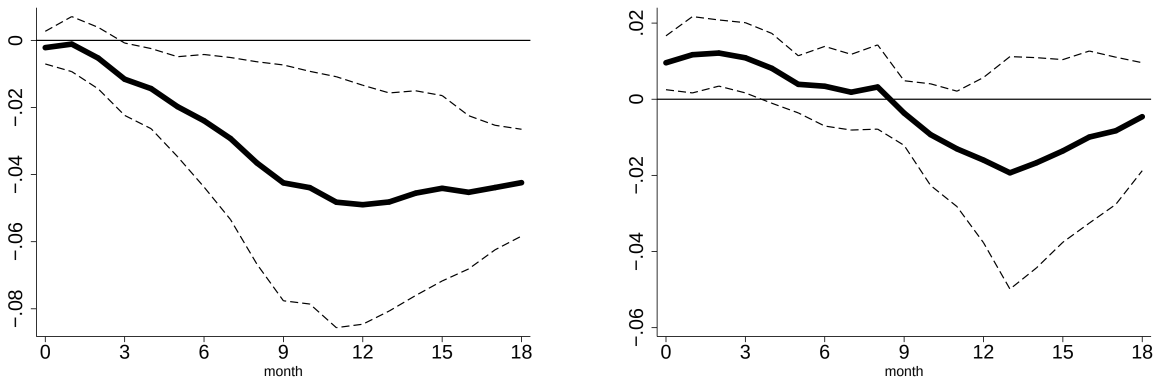
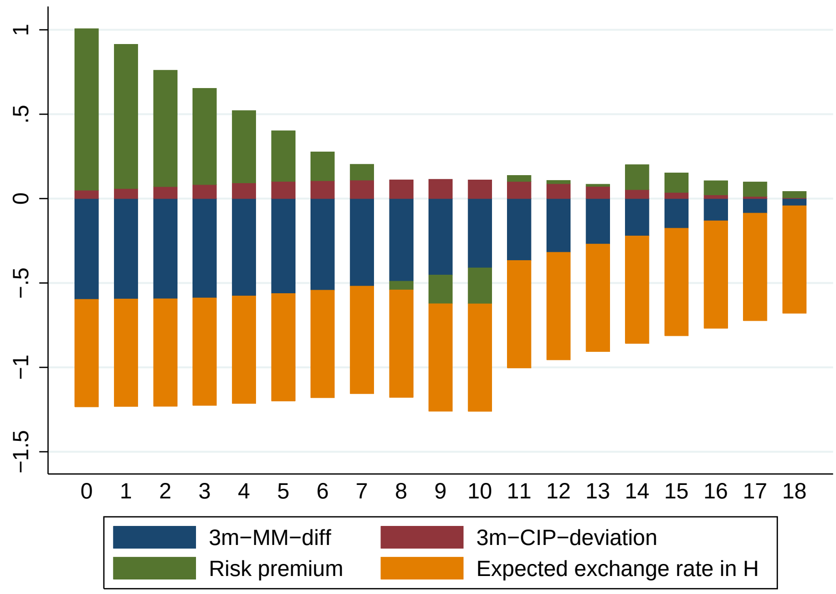


Figure 5: Decomposition of exchange rate response to QE shocks



Notes: The figure shows the decomposition of the exchange rate effect of a relative QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point into the transmission channels according to Equation (13).

Figure 6: Impulse responses of other euro area financial variables

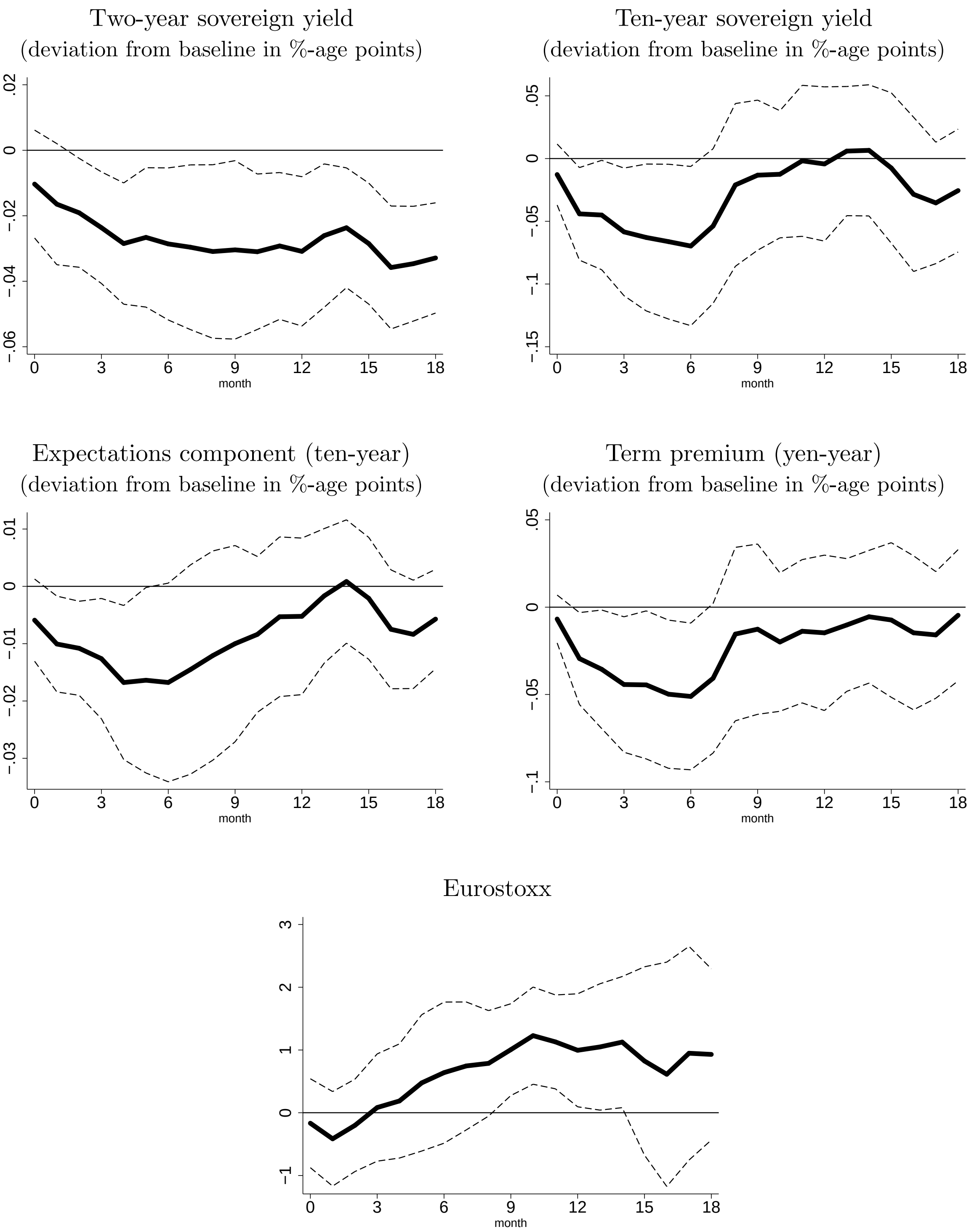


Figure 7: Impulse responses of other US financial variables

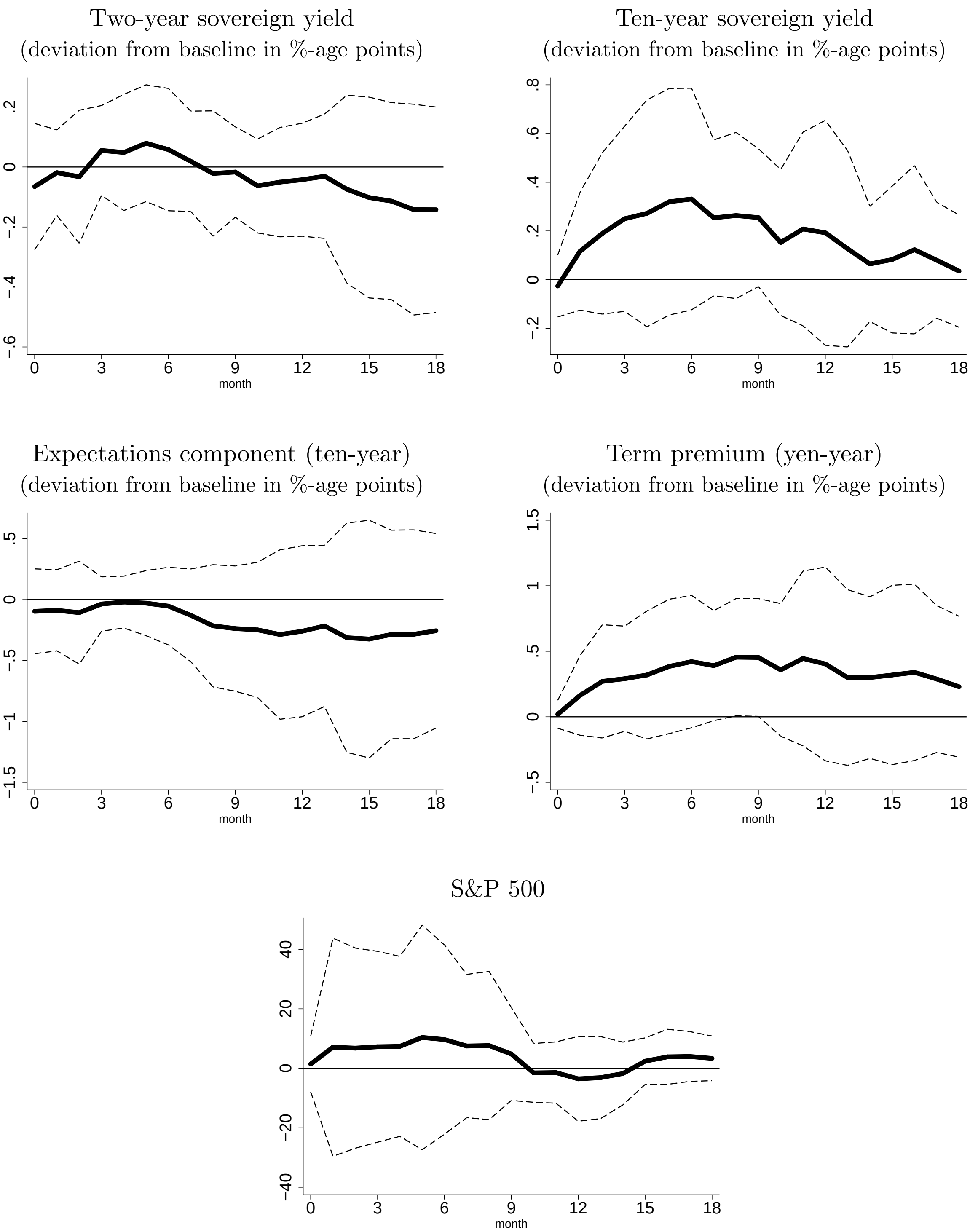


Figure 8: Impulse responses of real variables

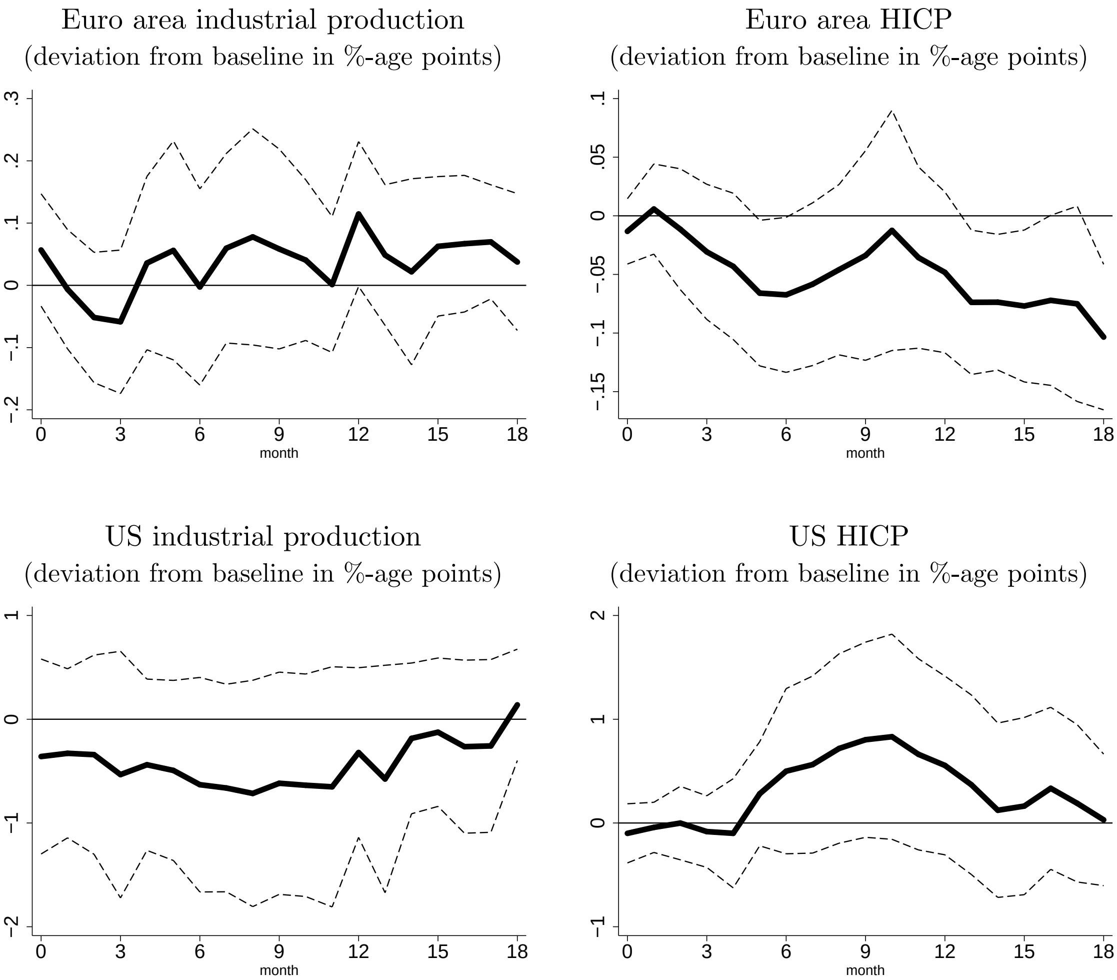


Figure 9: With controls $\boldsymbol{w}_{t-1+m}$, $m = 1, 2, \ldots, M$

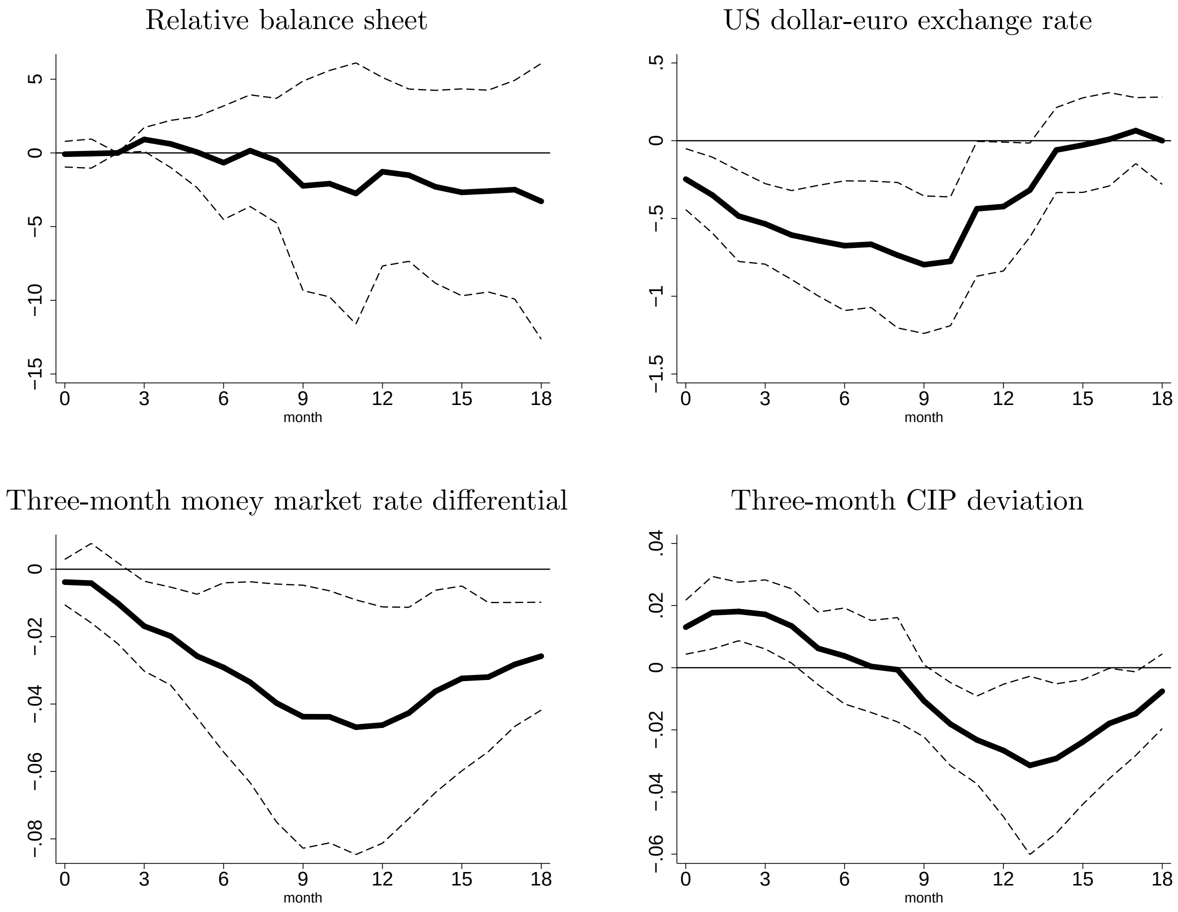


Figure 10: Balance sheet variable $BS_{t+3} - BS_{t-1}$

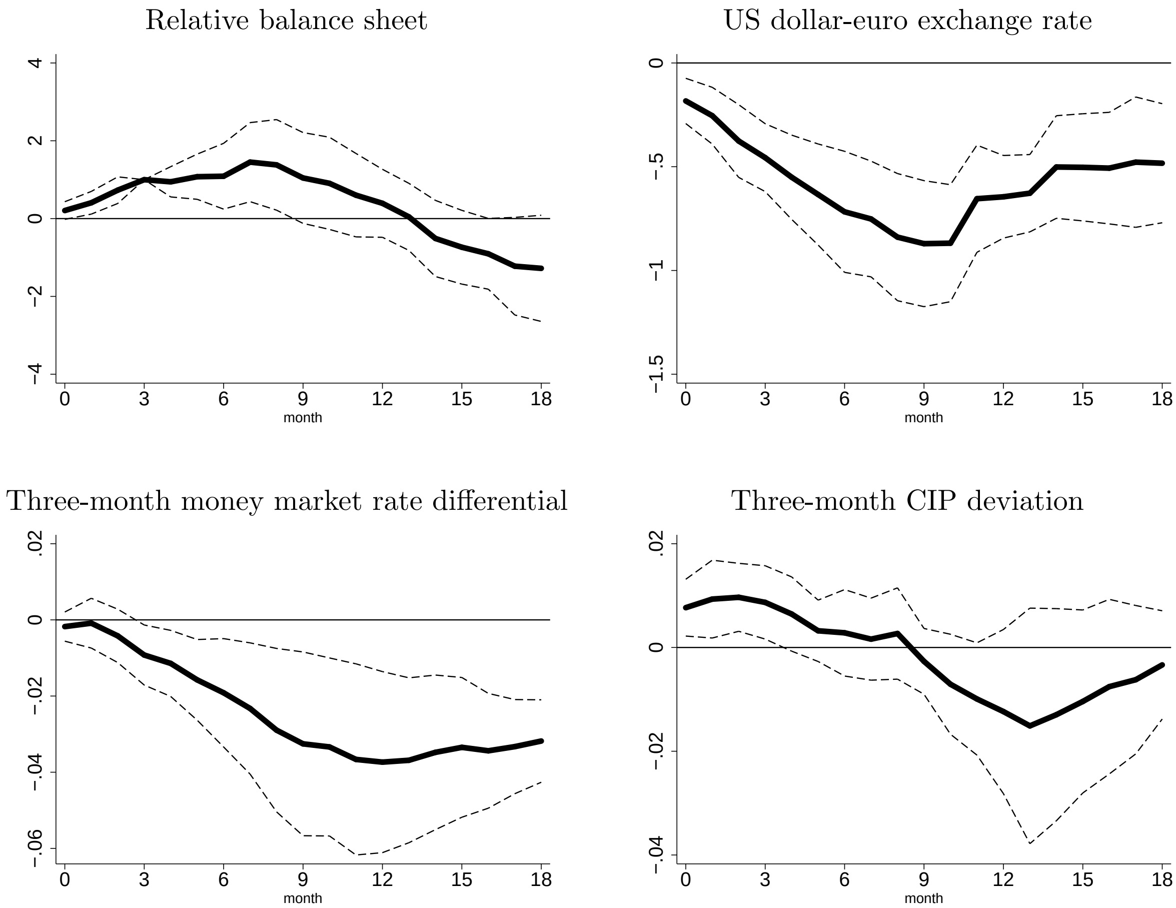


Figure 11: Controlling for lagged macro shocks

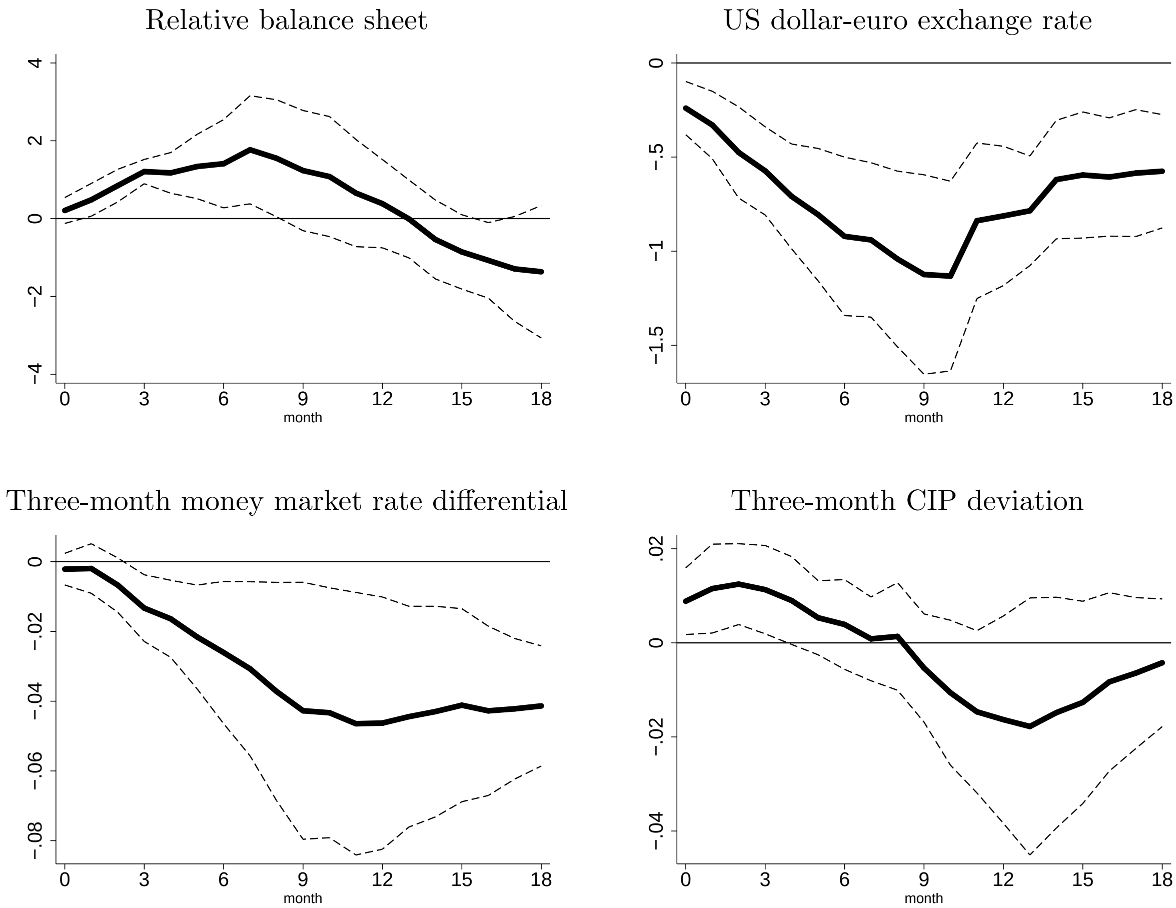


Figure 12: QE announcements weighted by stock market surprise on day of announcement

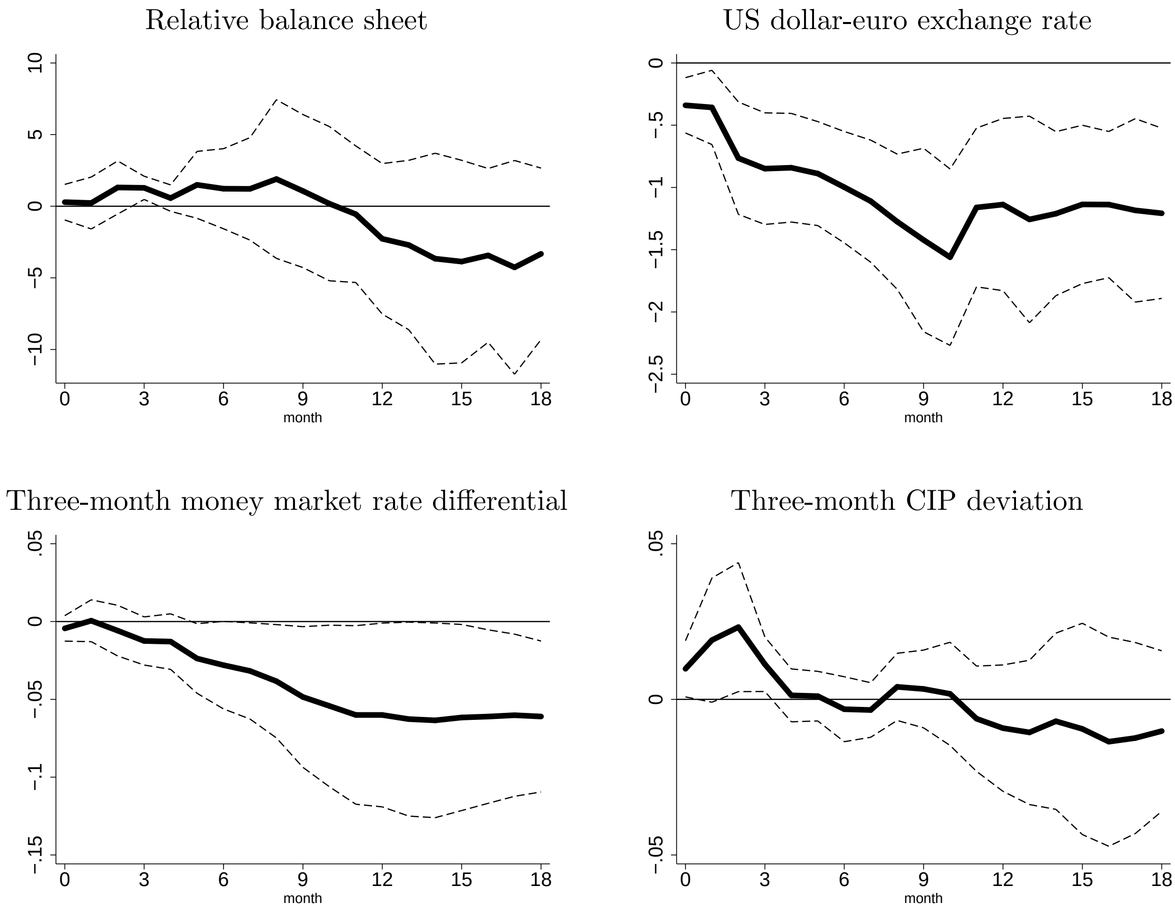


Figure 13: Narrative identification

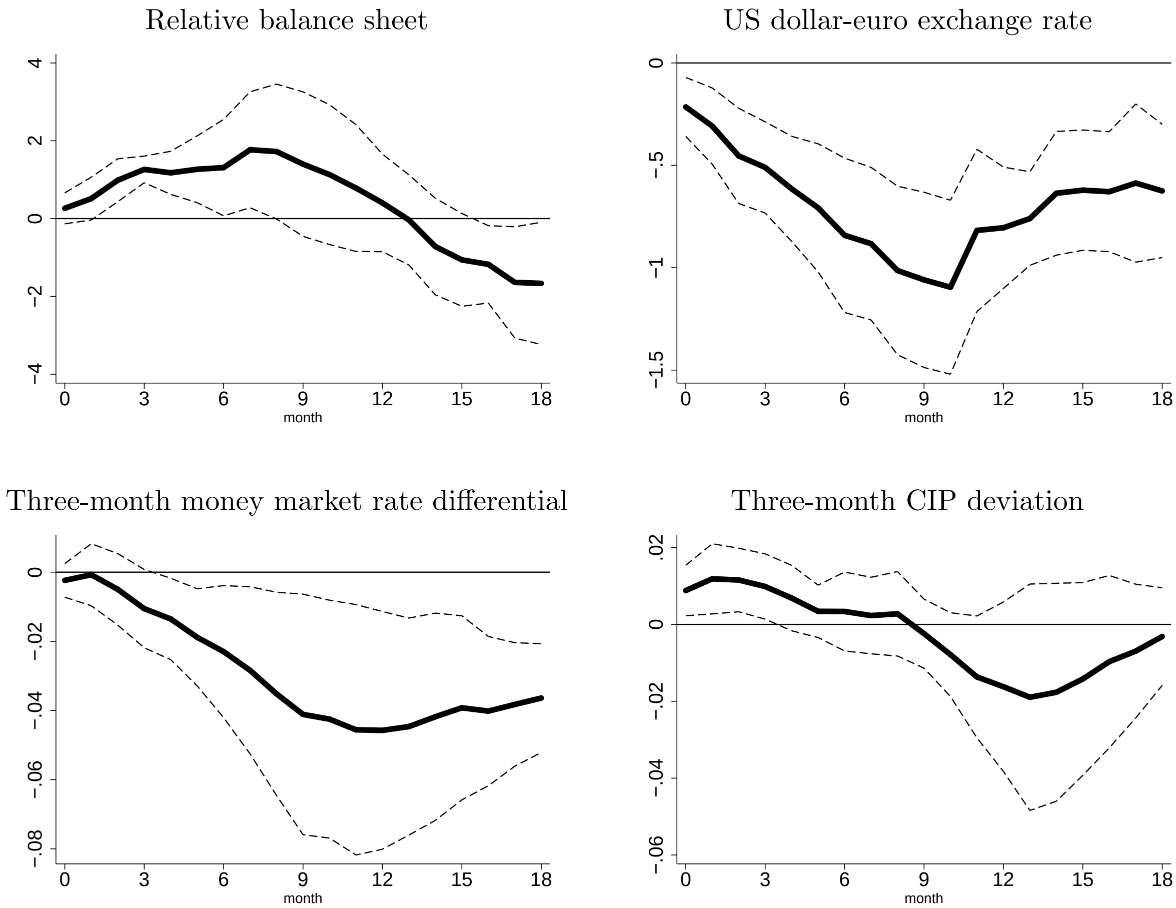


Figure 14: Ecluding APP announcements

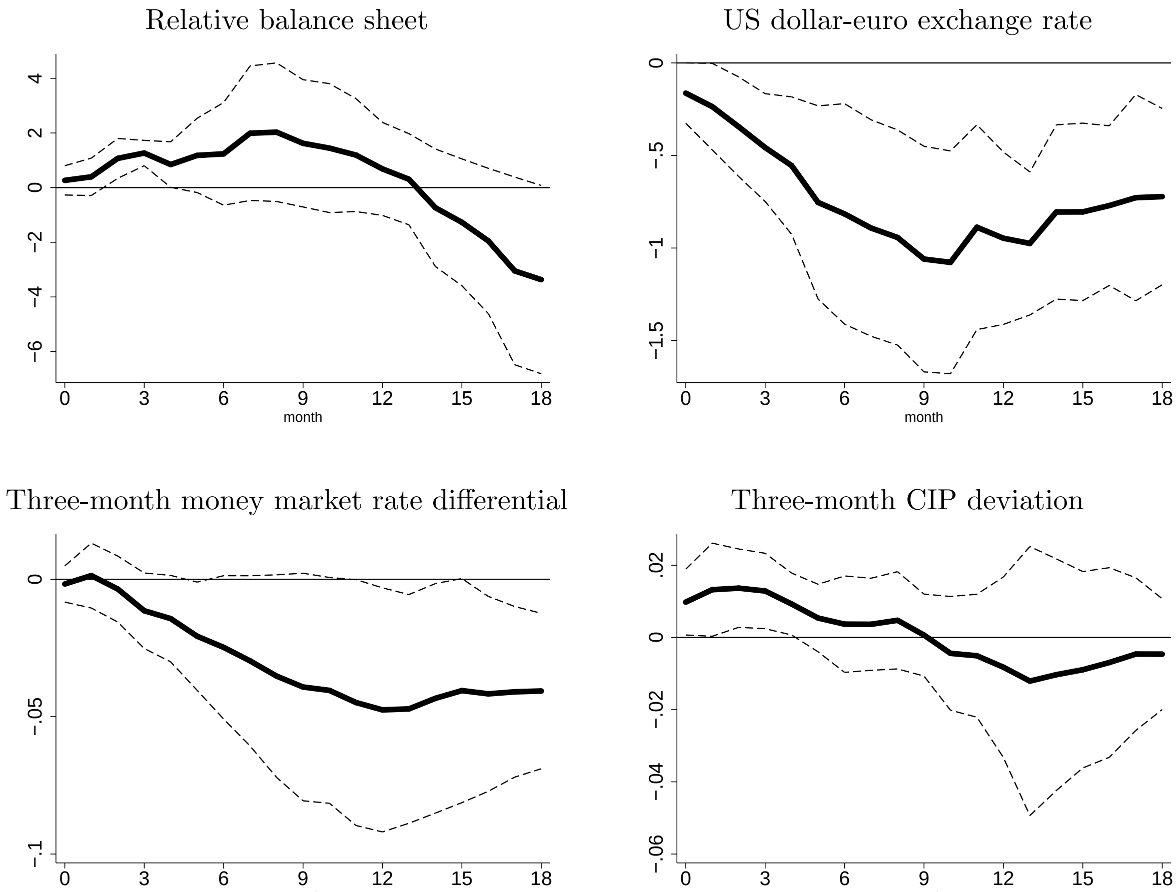


Figure 15: Weekly data, $(BS_{t+12} - BS_t)$

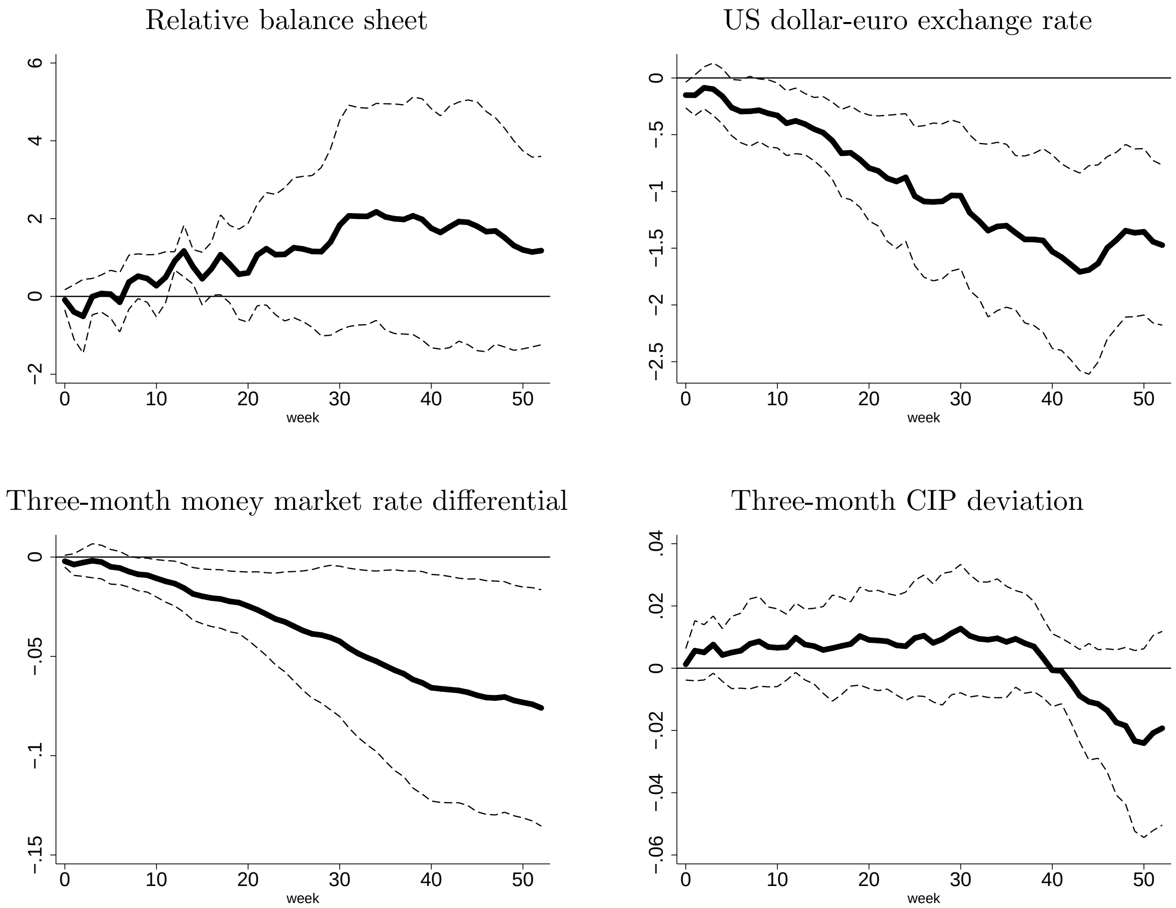


Figure 16: Weekly data: Exchange rate—Robustness