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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 with QE announcements in two-stage least squares regressions in order to account for their endogeneity. We find that QE measures have large and persistent effects on the exchange rate. The typical ECB or Federal Reserve expansionary QE announcement in our sample resulted in an increase in the relative balance sheet of about 20% and, in turn, in a persistent exchange rate depreciation of around 7%. 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 euro against the US dollar by reducing euro-dollar short-term money market rate differentials, by widening the cross-currency basis and by eliciting adjustments in "residual" deviations from interest parity. Changes in the expectations about the future monetary policy stance, reflecting the "signalling'" channel of QE, also contribute to the exchange rate response to QE shocks.

JEL Classification: F41

Keywords: QE Dynamic Effects, Signalling Channel of QE, CIP Deviations

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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 broad array of quantitative easing (QE) measures as an additional policy tool, which resulted in dramatic expansions of their balance sheets. For instance, the Federal Reserve was early in increasing the size of its balance sheet by purchasing large amounts of private and government securities between 2008 and 2012. The ECB initially implemented more modest asset purchase programs, but after the second half of 2011 greatly expanded its balance sheet by providing liquidity to the banking sector far beyond standard short-term maturities. By March 2012, the nominal size of the ECB's balance sheet was similar to that of the Federal Reserve (see the top panel of Figure B.1). 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, at the end of 2014 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 and raising it further thereafter. While at the time of writing the Federal Reserve is well past the peak recourse to unconventional monetary policy measures, the ECB has announced that it would examine options for a potential fresh round of QE. Interest in the effects of QE has thus hardly faded, with several policymakers also arguing that given the secular decline in the natural interest rate, QE may remain an important component of central banks' toolkit going forward (Constancio, 2017; Yellen, 2017). Deepening our understanding of the workings of QE is thus a central issue in monetary policy.

The exchange rate has been at the center stage in both academic and policy debates about the effectiveness, transmission channels and spillovers of QE (see, for example Rajan, 2013; Bernanke, 2015; Powell, 2018). That the size of the central bank's balance sheet and thereby the (relative) supply of monetary base may affect a currency's international value is a time-honored topic in open-economy macroeconomics; it has been extensively discussed already 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 B.1 suggests that there has been a correlation between the relative balance sheet of the ECB and the Federal Reserve and the US dollar-euro exchange rate (where a fall in the exchange rate in the bottom panel denotes a euro depreciation). In particular, expansions in the relative central bank balance sheet after announcements of QE measures have tended to be associated with depreciations in the corresponding currency. These correlations are of course silent about causality, and cannot be relied on to gauge the effectiveness or transmission channels of QE measures and to calibrate structural models accordingly.

Against this background, a large literature has emerged that is concerned with assessing the effects of QE, including on the exchange rate. On the one hand, the bulk of this literature has focused on the high-frequency and short-term effects of QE measures, typically by means of event studies that consider a narrow time window around QE announcements.[1] While this approach has provided evidence on the impact effects of QE announcements for a variety of asset prices, including exchange rates, it is less useful for shedding light on the persistence of the effects and the transmission channels of QE beyond the very short-term. On the other hand, a second strand of the literature has investigated the effects of QE at longer horizons.[2] However, few of these studies have focused on the impact of QE on the exchange rate and its transmission channels. And even if the exchange rate has been among the variables considered in some of these studies, several gaps remain. Specifically, the existing evidence on the effects of QE on the exchange rate in this strand of the literature stems from structural VAR models, which separately consider either Federal Reserve or ECB QE shocks, but never both together. Notably, the VAR approach also does not take into account the important fact that QE measures have been announced by central banks usually prior to their implementation, and that, as documented by event studies in the literature, forward-looking asset prices such as the exchange rate have reacted immediately to these announcements.

Our contribution in this paper fills these gaps. In particular, we estimate the effects of QE on the exchange rate at horizons that are relevant to inform policymakers and

[1] This literature has become too voluminous to do justice to all relevant contributions. For surveys of the literature see Bhattarai and Neely (2016) and Borio and Zabai (2016). See also Woodford (2012).

[2] See, for example, Bhattarai et al. (2018), Anaya et al. (2017), Chen et al. (2016), Bluwstein and Canova (2016), as well as Wieladek and Garcia Pascual (2016).

structural models, and we explore the transmission channels through which the effects materialize over time. In line with the monetary theory of the exchange rate as a relative price, 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. Specifically, our estimates imply that a typical expansionary QE announcement by either the ECB or the Federal Reserve in our sample resulted in an increase in the relative balance sheet of about 20% in the next nine months, and, in turn, in a persistent exchange rate depreciation of around 7%. Regarding the transmission channels, we find that a QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve persistently reduces the euro-dollar short-term money market rate differential. The effects of QE on short-term interest rate differentials result in part from liquidity effects in money markets, and in part from expectations of further monetary policy accommodation over the medium term — the so-called "signalling" channel of QE (see Woodford, 2012). Further supporting the existence of a "signalling" channel, we find that a QE shock which expands the ECB's balance sheet relative to that of the Federal Reserve shifts markets' expectations regarding "time-to-lift-off" farther into the future. Nevertheless, our results suggest that a sizable quantitative contribution stems from the effects of QE on "residual" deviations from interest parity (see Engel, 2016). While this term effectively captures all such unexplained deviations, its role is consistent with the recent models of currency risk premia in Gourinchas et al. (2019) and Greenwood et al. (2019). Finally, we document that an expansionary relative QE shock exacerbates limits to arbitrage in foreign exchange markets, as it widens CIP deviations reflected in the cross-currency basis. However, the response of CIP deviations accounts only for a negligible fraction of the overall effects of QE on the exchange rate.

We obtain our findings by developing an empirical approach that draws on elements from several strands of the literature. In particular, borrowing from the news shocks literature (Schmitt-Grohe and Uribe, 2012), we conceive QE measures that are announced in period t as shocks which are anticipated by agents to affect central banks' balance sheets in the current and future periods $t+m$, $m=0,1,\ldots,M$. We then show that while these

QE shocks may not be observed by the econometrician they can be proxied by future changes in central banks' balance sheets. In turn, we show that in the framework that we posit 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 to central bank balance sheets, rather than announcements, as the main variable of interest in our empirical framework because this allows us to establish a quantitative assessment of the effects of the ECB's and the Federal Reserve's QE programs on the exchange rate. In particular, our framework allows us to determine an elasticity that reflects the change in the exchange rate implied by an average QE measure that changes the relative central bank balance sheet by a given magnitude.

An important caveat is that given our focus on *actual increases* in the overall size of central banks' balance sheets, we do not explicitly consider the effects of changes in their composition, either in terms of maturity (e.g. short or long-dated securities) or origination of the central bank asset holdings (e.g. claims on governments, firms, or banks, or even on different jurisdictions in case of the ECB). Nor do we consider measures mostly aimed at ruling out self-fulfilling expectations without a material impact on the central bank balance sheet, such as the ECB Outright Monetary Transactions (OMT). On the one hand, this focus does not reflect an assumption that the composition of the central bank's balance sheet, or policy measures which did not materially increase it (such as the Federal Reserve's "Operation Twist" or the ECB's OMT), would not impact exchange rates. Rather, we do not explore the effects of these policies or of particular compositions of the balance sheet, because our analytical framework is not devised to specifically account for them.[3] On the other hand, our approach does capture on average the effects across the different kinds of balance sheet expansions (which have varied in their composition and size) actually implemented by the ECB and the Federal Reserve. Hence, our results are still relevant for improving the understanding and calibration of the exchange rate impact across QE measures.

More technically, we estimate the effects of QE on the US dollar-euro exchange rate using local projections (Jorda, 2005). We derive a theoretically-consistent local projection

[3]See Swanson (2011) for evidence on the effects of the original "Operation Twist" and QE2.

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. In order to address the endogeneity of the central banks' relative balance sheet — which we use as proxy for the QE shocks not observed by the econometrician — 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, 2018). 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, guiding the inference, the choice of control variables and their timing. We also pay great attention to model specification tests, including on instrument validity and power. An appealing feature of our empirical framework is that it allows us to take into account changes in central banks' balance sheets that occur both contemporaneously and up until relatively long horizons in the future in order to proxy QE shocks; in contrast, the existing literature typically conceives QE shocks as contemporaneous changes in the central bank balance sheet. Given that the exchange rate is a forward-looking variable that is affected by expected changes in future fundamentals, our framework is especially well-suited to assess the dynamic effects of QE on exchange rates. Finally, we explore several robustness checks related to variations of the identification of QE shocks (e.g. by exploiting stock price changes on the day of the announcements) as well as various aspects of the regression specification and data frequency (e.g. we show that results are broadly unchanged when, instead of monthly, we use noisier weekly data).

Some previous work has explored the dynamic effects of QE on exchange rates in VAR models. A first set of studies has focused on US QE shocks. On the one hand, Bhattarai et al. (2018) and Anaya et al. (2017) identify US QE shocks using the Federal Reserve's balance sheet, finding that these shocks significantly appreciate emerging market economies' currencies. On the other hand, Chen et al. (2016) as well as Punzi and Chantapacdepong (2017) model QE shocks as VAR innovations to US term or corporate bond spreads and to a shadow short rate, respectively.[4] While Chen et al. (2016) find

[4]Specifically, Bhattarai et al. (2018) identify QE shocks with non-recursive short-run restrictions, while

only minor effects of US QE shocks on foreign exchange pressure indices, Punzi and Chantapacdepong (2017) find an appreciation of Asian currencies.

A second set of VAR studies has focused instead on the ECB. On the one hand, Bluwstein and Canova (2016) and Wieladek and Garcia Pascual (2016) focus on ECB asset purchases, finding that the euro broadly depreciated against European currencies in response to QE shocks.[5] On the other hand, Babecka Kucharcukova et al. (2016) and Feldkircher et al. (2019) model ECB QE shocks as structural innovations to a monetary conditions index and the euro term spread, respectively, finding mixed responses of European economies' exchange rates to these shocks.

Our paper differs from the existing literature in several respects. First, the existing evidence on the exchange rate effects of QE essentially stems from VAR models which separately estimate either Federal Reserve or ECB QE shocks. However, given that the exchange rate is a relative (asset) price, it seems preferable to consider ECB and Federal Reserve QE simultaneously, in particular in order to reduce risks of omitted variable bias and to improve efficiency of estimation. Second, the existing literature relies on identification approaches very different from ours, based on (usually contemporaneous) zero or sign-restrictions on central bank balance sheet variables and some interest rates, mostly without taking into account information from central bank QE announcements — which event studies have shown affect exchange rates on impact. Finally, none of the existing work zooms in on the effects of QE on the exchange rate, exploring in detail the transmission channels.

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 the presentation of our results in Section 4. Section 5 briefly discusses extensive robustness checks (relegated to the web appendix), and Section 6 concludes.

Anaya et al. (2017) use sign restrictions; both Chen et al. (2016) as well as Punzi and Chantapacdepong (2017) instead rely on recursive identification schemes.

[5] Specifically, Bluwstein and Canova (2016) estimate two-country, mixed-frequency VAR models, in which identification is based on contemporaneous zero (exclusion) restrictions; Wieladek and Garcia Pascual (2016) use a mix of zero and sign restrictions.

2. A framework for the estimation of the effects of QE on the exchange rate

In this section we derive 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, in Section D in the web appendix we 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 generalized 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. We then show below 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 generalized UIP conditions for periods $t+h$ and $t-1$.

2.1. Deriving a local projection equation for the exchange rate

In the web appendix we derive the following generalized UIP condition for the euro-dollar spot exchange rate s_t—defined as the price of one euro in terms of the amount of US dollars—in the presence of CIP deviations:

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

where $dr_t \equiv r_t^{€} - r_t^{\$}$ is the one-period risk-free euro-dollar interest rate differential, π_t is a currency risk premium, and λ_t captures (log) CIP deviations as follows:

$$\lambda_t \equiv r_t^{€} - \left(r_t^{\$} - f_{t,t+1} + s_t\right). \tag{2}$$

Notice that our definition of the CIP deviation coincides with the market definition of the cross-currency basis, except for having the *opposite* sign (see, for example, Du et al., 2018). Specifically, in case $\lambda_t > 0$, CIP deviations arise because the "cash" one-period risk-free return on investing one euro is larger than the "synthetic" one-period risk-free return that could be obtained by investing one euro in the "cash" dollar market (by changing the euro at the spot exchange rate s_t and swapping the returns back into euro at the forward exchange rate $f_{t,t+1}$).[6]

Iterating forward Equation (F.11) for T periods and applying the law of iterated expectations yields:

$$s_t = E_t s_{t+T} + \sum_{j=0}^{T-1} E_t dr_{t+j} - \sum_{j=0}^{T-1} E_t \lambda_{t+j} + \sum_{j=0}^{T-1} E_t \pi_{t+j}, \tag{3}$$

which states that the spot exchange rate in period t is determined by current and expected future fundamentals — i.e. short-term interest rate differentials, risk premia, CIP deviations, and the expected value of the exchange rate at horizon T. Equation (F.12) 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. For instance, the classic monetary approach to exchange rate determination provides a possible channel through which QE can affect the exchange rate to the extent that changes in the relative supply of high-powered money have liquidity effects on current and expected money-market rates (Dornbusch, 1976), affect CIP deviations in the presence of frictions as those discussed above or even affect currency risk premia, e.g. through a portfolio balance channel.

Likewise, QE can impact the exchange rate to the extent that it affects the expectations component of long-term (i.e. the sum of expected short-term) interest rates and/or if term premia are correlated with currency risk premia, as in Gourinchas et al. (2019) and Greenwood et al. (2019). The effect of QE on the exchange rate through the expectations component of long-term interest rates is usually referred to as the "signalling" channel (Woodford, 2012). Specifically, under the signalling channel QE measures convey information about future monetary policy rates. If effective, it is clear from Equation (F.12) that the signalling channel of QE is in general also reflected by changes in the expectation of the exchange rate at some longer horizon T.

Consider the generalized UIP condition in Equation (F.12) and subtract from both

[6] As shown in the web appendix, in levels we would have the following relation:

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

where $\lambda_t > 0$ arises from borrowing constraints in cash euro markets being tighter than in dollar cash markets.

sides the corresponding equation lagged by one period:

$$\begin{aligned} s_t - s_{t-1} = &- dr_{t-1} + \lambda_{t-1} - \pi_{t-1} \\ &+ E_t s_{t+T} - E_{t-1} s_{t+T} + \sum_{j=0}^{T-1} \left(E_t dr_{t+j} - E_{t-1} dr_{t+j} \right) \\ &- \sum_{j=0}^{T-1} \left(E_t \lambda_{t+j} - E_{t-1} \lambda_{t+j} \right) + \sum_{j=0}^{T-1} \left(E_t \pi_{t+j} - E_{t-1} \pi_{t+j} \right). \end{aligned} \tag{4}$$

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 $E_{t-1}(\boldsymbol{\varepsilon}_t) = 0$, which is also orthogonal to all lagged terms in the first line of Equation (4). Assuming linearity, we can replace the changes in expectations by the impact of structural shocks and write Equation (4) as:

$$s_t - s_{t-1} = -dr_{t-1} + \lambda_{t-1} - \pi_{t-1} + \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_t, \tag{5}$$

where

$$\begin{aligned} \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_t \equiv & E_t s_{t+T} - E_{t-1} s_{t+T} + \sum_{j=0}^{T-1} \left(E_t dr_{t+j} - E_{t-1} dr_{t+j} \right) \\ &- \sum_{j=0}^{T-1} \left(E_t \lambda_{t+j} - E_{t-1} \lambda_{t+j} \right) + \sum_{j=0}^{T-1} \left(E_t \pi_{t+j} - E_{t-1} \pi_{t+j} \right). \end{aligned} \tag{6}$$

Analogously to the difference between periods t and $t-1$ in Equation (4), for the difference between the exchange rate in periods $t+h$ and $t-1$ we have

$$s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_{t+h} + \boldsymbol{\alpha}_1' \boldsymbol{\varepsilon}_{t+h-1} + \ldots + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t. \tag{7}$$

where

$$
\begin{aligned}
\omega_{t-1,h} \equiv & - dr_{t-1} + \lambda_{t-1} - \pi_{t-1} \\
& - \sum_{j=1}^{h-1} E_{t-1} dr_{t+j-1} + \sum_{j=1}^{h-1} E_{t-1}\lambda_{t+j-1} - \sum_{j=0}^{h-1} E_{t-1}\pi_{t+j-1}.
\end{aligned} \tag{8}
$$

Taking expectations of Equation (7) as of period t yields

$$
E_t s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t, \tag{9}
$$

which shows that the coefficients $\boldsymbol{\alpha}_h$ represent the impulse response of the exchange rate at horizon h to the structural shocks $\boldsymbol{\varepsilon}_t$ occurring in period t. Ordinary least squares (OLS) estimation of the local projection regression

$$
s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t + \nu_{t,h}, \tag{10}
$$

with

$$
\nu_{t,h} \equiv \sum_{j=0}^{h-1} \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_{t+h-j}, \tag{11}
$$

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

Before we introduce QE shocks in Equation (10), it is worthwhile to highlight two issues. First, departures from rational expectations may imply that the forecast errors $\boldsymbol{\varepsilon}_t$ in Equation (5) are forecastable (see Iovino and Sergeyev, 2018, for an application to QE). In this case, we would not be able to interpret $\boldsymbol{\varepsilon}_t$ as structural shocks. However, in this case one could project the forecast errors on lagged variables in order to obtain the structural shocks. Hence, in the context of our paper one would have to include additional lagged variables on the left-hand side of Equation (6) in order to isolate the structural shocks. And as we explain in more detail in Section 3 below, in the empirical specification of our regressions we do include lags of a number of variables, even if this would not be strictly necessary under rational expectations. Second, some evidence in the empirical literature on exchange rates suggests that “UIP does not hold” (Fama, 1984). However, notice that what the "failure of UIP" refers to in this literature is that OLS estimation of Equation (F.11) produces a coefficient estimate on the interest rate differential different from unity (see Engel, 2014, for a survey), rather than UIP not holding as a no-arbitrage relation. Most importantly, this notion of "failure of UIP" does not affect the derivation of Equation (5).

2.2. Introducing QE shocks

In order to see how the local projection in Equation (10) can be used to estimate the effects of QE on the exchange rate we first conceptualize the notion of QE shocks in our context. Specifically, we first partition the vector of structural shocks into $\boldsymbol{\varepsilon}_t = (\varepsilon_t^{qe}, \boldsymbol{e}_t')'$, such that ε_t^{qe} is a QE shock, and $\boldsymbol{e}_t$ includes non-QE structural shocks such as conventional monetary policy shocks or money demand shocks. Then, borrowing from the news shock literature (see, for example, Schmitt-Grohe and Uribe, 2012) and again assuming linearity, we posit a QE shock ε_t^{qe} such that

$$\varepsilon_t^{qe} = \sum_{m=0}^{M} \eta_{t+m|t}, \tag{12}$$

where $\eta_{t+m|t}$ represents a QE shock that materializes in period t but that is anticipated by agents to affect the central bank balance sheet through asset purchases only in period $t+m$. Accordingly, we assume that the central bank balance sheet evolves as

$$\Delta BS_t = \delta_0 + \sum_{m=0}^{M} \eta_{t|t-m} + \boldsymbol{\delta}'\boldsymbol{e}_t. \tag{13}$$

As we are interested in the effects of QE on the exchange rate and as the exchange rate is a relative price, we interpret ε_t^{qe} as a *relative* QE shock. Specifically, ε_t^{qe} is positive when a QE shock occurs in the euro area in the absence of an analogous shock in the US; conversely, ε_t^{qe} is negative when a QE shock occurs in the US in the absence of an analogous shock in the euro area. Equation (13) hence specifies the evolution of the *relative* central bank balance sheet, that is the balance sheet of the ECB relative to that of the Federal Reserve.

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 (10) as

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} \eta_{t+m|t} \right) + \omega_{t-1,h} + \boldsymbol{a}_h' \boldsymbol{e}_t + \nu_{t,h}. \tag{14}$$

The intuition underlying Equation (14) is that because the exchange rate is a forward-looking asset price it will respond to a relative QE shock that materializes in period t, even if it involves asset purchases that will be — and are anticipated by agents to be — carried out in the future.

Notice that the analytical framework represented by Equation (14) does not take a stance on the channels through which QE shocks affect the exchange rate, and, as $\{\alpha_h^{qe}\}_{h=0,1,...}$ may be zero, not even on whether QE shocks impact exchange rates at all. Notice also that the analytical framework for the exchange rate we consider in this paper differs from the approaches in the existing time-series literature on the effects of QE discussed in the Introduction, which do not take into account the component of QE shocks that is reflected in anticipated future changes in central banks' balance sheets, that is $\eta_{t+m|t}$ with $m > 0$.[7] We therefore believe that our framework is better suited to assess the exchange rate effects of QE than the typical VAR framework used in the existing literature.

2.3. Proxying QE shocks by central bank balance sheet changes

Estimating the effects of QE shocks on the exchange rate in Equation (14) is of course complicated by the fact that the former are not observed by the econometrician. However, given Equation (13) we can proxy the unobserved relative QE shocks by changes in the relative central bank balance sheet. In particular, we can substitute the QE shocks in the

[7]Exceptions are Boeckx et al. (2017) as well as Gambacorta et al. (2014), who impose sign restrictions on impact and one month after the impact period. Only Weale and Wieladek (2016) consider the expected amount of asset purchases expected over the full horizon of the relevant QE programs. However, none of these studies explores the exchange rate effects of QE.

local projection of the exchange rate in Equation (14) using Equation (13) and

$$\eta_{t+m|t} = \Delta BS_{t+m} - \left(\delta_0 + \sum_{\substack{k=0 \\ k\neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \boldsymbol{e}_{t+m} \right),$$

to obtain

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} \Delta BS_{t+m} \right) + \omega_{t-1,h} - \alpha_h^{qe}(M+1)\delta_0 + \zeta_{t,h}, \tag{15}$$

where

$$\zeta_{t,h} \equiv -\alpha_h^{qe} \boldsymbol{\delta}' \sum_{m=0}^{M} \boldsymbol{e}_{t+m} - \alpha_h^{qe} \sum_{m=0}^{M} \sum_{\substack{k=0 \\ k\neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{a}_h' \boldsymbol{e}_t + \nu_{t,h}. \tag{16}$$

Notice that the term $\sum_{m=0}^{M} \sum_{k=0,\, k\neq m}^{M} \eta_{t+m|t+m-k}$ in Equation (16) only contains future and lagged but no contemporaneous QE shocks. It is also worthwhile to stress that we are positing that future changes in the relative balance sheet (as anticipated by QE shocks) may affect current and future exchange rates. In this sense our theoretical framework is consistent with the literature on the difficulty of forecasting exchange rates in real time and out-of-sample (Meese and Rogoff, 1983).

2.4. Two-stage least squares regression framework

As can be seen from Equation (13) the variable of interest, $\sum_{m=0}^{M} \Delta BS_{t+m}$, is endogenous in Equation (15) due to its correlation with the error term $\zeta_{t,h}$.[8] Intuitively, central banks' balance sheets change not only in response to QE shocks, but also in response to non-QE shocks $\boldsymbol{e}_t$, such as money demand and conventional monetary policy shocks. In order to address this endogeneity, as in Jorda et al. (2015) and Ramey and Zubairy (2018), we adopt a local projection two-stage least squares approach using QE announcements as instruments for $\sum_{m=0}^{M} \Delta BS_{t+m}$ in Equation (15).[9] In particular, we assume that ECB and Federal Reserve QE announcements a_t^{ECB} and a_t^{Fed} are related to anticipated relative

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

[9] The use of external instruments was originally introduced in the VAR context by Stock and Watson (2012) as well as Mertens and Ravn (2013). See Stock and Watson (2018) for a survey and discussion.

QE shocks according to

$$\eta_{t+m|t} = \sigma_m + \mu_m^{\text{ECB}} a_t^{\text{ECB}} + \mu_m^{\text{Fed}} a_t^{\text{Fed}} + u_{t,m}, \quad m = 0, 1, \ldots, M. \tag{17}$$

The intuition for Equation (17) is that a QE announcement in period t is generally followed by changes in the relative central bank balance sheet m periods in the future. Summing Equation (17) over horizons $m = 0, 1, \ldots, M$ yields

$$\sum_{m=0}^{M} \eta_{t+m|t} \quad = \quad \sigma + \mu^{\text{ECB}} a_t^{\text{ECB}} + \mu^{\text{Fed}} a_t^{\text{Fed}} + u_t. \tag{18}$$

Summing the relative balance sheet in Equation (13) analogously yields

$$\sum_{m=0}^{M} \Delta BS_{t+m} \quad = \quad (M+1)\delta_0 + \sum_{m=0}^{M} \eta_{t+m|t} + \sum_{m=0}^{M} \sum_{\substack{k=0 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \sum_{m=0}^{M} \boldsymbol{e}_{t+m}, \tag{19}$$

which shows that our variable of interest in Equation (15) that is affected by endogeneity, $\sum_{m=0}^{M} \Delta BS_{t+m}$, is correlated with the sum of future anticipated QE shocks $\sum_{m=0}^{M} \eta_{t+m|t}$, which can be forecasted by QE announcements in Equation (18).

Against the background of Equations (15), (18) and (19), we thus consider a two-stage least squares regression approach in which the second-stage regression is given by Equation (15) and the first-stage regression by

$$\sum_{m=0}^{M} \Delta BS_{t+m} = \varpi + \theta^{\text{ECB}} a_t^{\text{ECB}} + \theta^{\text{Fed}} a_t^{\text{Fed}} + \omega_{t-1,h} + \xi_t. \tag{20}$$

Our identifying assumptions are that the instruments for the relative balance sheet variable $\sum_{m=0}^{M} \Delta BS_{t+m}$ in Equation (15) 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 (16), i.e. with contemporaneous and future non-QE structural shocks, $\boldsymbol{e}_{t+m}$, $m = 0, 1, \ldots, M$, future and past QE shocks $\eta_{t+m|t+m-k}$, $k, m = 0, 1, \ldots, M$, $k \neq m$, as well as future structural shocks in $\nu_{t,h}$ defined in Equation (16) (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 (20) (instrument relevance)

Notice that (ii) is satisfied already when $\mu_m^{\text{ECB}} \neq 0$ and/or $\mu_m^{\text{Fed}} \neq 0$ in Equation (17) for *some* horizon m. This contrasts with the approaches in the existing literature, which typically require the stronger assumption $\mu_0^j \neq 0$ for identification.

In our estimations, we formally test the validity of these assumptions by means of the Hansen J-test of over-identification (a test for the exogeneity/validity of the instruments) and the Kleibergen and Paap (2006) test of under-identification (a test for instrument relevance). We also report the results of tests for weak instruments by Montiel Olea and Pflueger (2013) based on the effective F-statistic as implemented in Stata by Pflueger and Wang (2015).[10] We discuss and explore some possible concerns with these assumptions in robustness checks.[11]

Finally, one may wonder why we do not just use Equation (17) to substitute the QE shocks with QE announcements in the local projection for the exchange rate in Equation (14) instead of adopting the more complicated two-stage least squares framework in which changes in the relative central bank balance sheet proxy unobserved QE shocks. In particular, the former approach would spare us from endogeneity problems and thereby substantially facilitate the analysis. However, doing so would entail an important limitation regarding the interpretation of our estimates. Specifically, in our two-stage least squares framework the impulse response of the exchange rate represents the impact of a QE shock that raises the relative central bank balance sheet by one percentage point

[10]Stock and Watson (2018) discuss an additional "lead/lag exogeneity" requirement for consistent estimation with local projections with external instruments. Here this requires that QE announcements must be uncorrelated with past structural — such as demand and risk — shocks. We address the issue of "lead/lag exogeneity" by including variables that reflect the shocks to which the QE announcements might be responding as controls in the second-stage regression (Jorda et al., 2015; Stock and Watson, 2018). See Section 3 for details.

[11]There is potential correlation between the sum of lagged expected future UIP fundamentals in $\omega_{t-1,h}$ and $\zeta_{t,h}$ defined in Equations (8) and (16), respectively. Specifically, $\zeta_{t,h}$ involves past QE shocks, which in general impact the future expected values of UIP fundamentals. However, in the regression specification we include several lagged variables as controls—-to proxy for terms in $\omega_{t-1,h}$—and, in particular, lagged QE announcements $a_{t-\ell}^j$, $\ell > 0$, $j \in \{Fed, ECB\}$. These lagged QE announcements generally pick up the lagged QE shocks in $\zeta_{t,h}$, and hence reduce any potential correlation between the lagged QE shocks in $\zeta_{t,h}$ and the lagged future expected UIP fundamentals in $\omega_{t-1,h}$.

over M months. In contrast, if we replaced the unobserved QE shocks by the announcements in the local projection for the exchange rate in Equation (14) using Equation (17), we would not be able to interpret the size of the QE shock in terms of a balance sheet expansion of a particular amount.

3. Empirical specification

3.1. Central banks' balance sheets and controls

Since we are interested in the effects of QE measures introduced in the wake of the global financial crisis and its aftermath, our sample spans the time period from November 2008 to April 2019.[12] Our analysis is carried out using data sampled at the monthly frequency; we consider weekly data in robustness checks. We transform the data for financial variables available at higher frequencies to monthly observations by calculating averages over daily or weekly data.

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 (balance sheet data are obtained from Haver). The variable $\sum_{m=0}^{M} \Delta BS_{t+m}$ then represents the percentage-points difference between the nominal growth rates of the ECB's and the Federal Reserve's balance sheets between periods $t+M$ and $t-1$. Approximately, this equals the percentage point change of the relative balance sheet between periods $t+M$ and $t-1$. We choose $M = 9$ for the baseline, given that the QE measures announced by the ECB and the Federal Reserve we consider in this paper and discuss below involved continued asset purchases over at least several months.

We proxy the variables in the vector $\omega_{t-1,h}$ that includes period-t–1 values and period-$t-1$ expectations of future values of the UIP fundamentals by lags of the policy rate, three-month money-market and two-year sovereign rate differentials, CIP deviations, the CitiGroup Macroeconomic Surprise indices, and the VIX; moreover, as suggested by Stock and Watson (2018), in the vector $\omega_{t-1,h}$ we also include the lags of our instruments given by the ECB and Federal Reserve QE announcements. For the respective policy rates we

[12]The working paper version of this paper explores the time period from January 2009 to December 2017.

use the Federal Funds target rate as well as the ECB deposit facility rate (DFR).[13] The data for these variables are obtained from Haver; the only exception is the data for the CIP deviation, for which we use the three-month cross-currency basis from Bloomberg multiplied by minus one in order to align its definition with that of the CIP deviation in this paper (see Section A in the web appendix). We consider three-month rather than one-month money market rates for consistency, as Bloomberg does not provide data for the one-month cross-currency basis.

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 the first-stage regression. Intuitively, our identification assumption here is that QE shocks do not contemporaneously affect the policy rate differential. Notice that this has to be almost trivially true, because (i) both the policy rate and the balance sheet are under the control of the central bank and (ii) the technicalities 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.

3.2. 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 release information about asset purchases or credit easing programs. Tables A.1 and A.2 report the ECB and Federal Reserve QE announcements we consider. The dates in question are assigned to their respective calendar month t.[14] Most of the announcements of the Federal Reserve QE measures are taken

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

[14]The indicator variables also equal unity when there is more than one announcement in a given month, implying that effectively there is only one monthly announcement. This occurs twice in our dataset in

from Rogers et al. (2014). However, we exclude some that do not fit our methodology. In particular, we only consider announcements of QE measures 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 OMT 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 sterilized 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 in the weighted average maturity of its asset holdings but did not expand its balance sheet. As can be seen from Equations (13) and (17), including these QE announcements in our analysis would reduce the power of our instruments for the change in the relative central bank balance sheet in the first-stage regression. It should be noted, however, that our focus on announcements of QE measures that had a tangible impact on central banks' balance sheets does *not* reflect an assumption that measures such as OMT or "Operation Twist" did not impact the exchange rate. Rather, we just do not explore their effects because our analytical framework is not devised to account for them. Nevertheless, our approach still captures on average the effects across the different kinds of QE measures (which have differed in their composition and size) actually carried out in our sample by the ECB and Federal Reserve. Finally, we add the four dates marked with an asterisk in Table A.2 as these foreshadowed Federal Reserve balance sheet expansions.[15] The ECB announcements are taken from the ECB's website.

Tables A.1 and A.2 also report the changes in the Eurostoxx and S&P500 stock price indices as well as German and US ten-year government bond yields on the days of the announcements. In most cases, changes in these asset prices were notable, suggesting that they featured at least some unexpected, surprise component. In a robustness check, we

the case of Federal Reserve announcements in December 2008 and October 2010. When we re-estimate our model at the weekly frequency in Section 5 we consider announcements in the same month separately.

[15] In the web appendix we document that our results are not sensitive to dropping these additional four dates.

exploit the response of asset prices on the day of announcement to weigh QE measures based on their surprise component, and, following Jarocinski and Karadi (2019), to better distinguish between expansionary QE shocks and negative central bank information shocks.

An extension to the use of the QE announcement dummies that would improve the power of our instruments in the first-stage regression in Equation (20) would be to consider a weighting by the announced amounts of purchases (see Weale and Wieladek, 2016, for QE in the UK and the US). However, the size of the QE measures in question was not known on the date of the announcement in several cases. For example, in the case of various exceptional liquidity operations conducted by the ECB, the overall size of the measures depended on take-up by banks, rather than being determined by the ECB. Also, some of the QE measures such as the ECB's APP were open ended, so that the total amount of purchases could not possibly have been known in advance.

4. The effects of ECB and Fed QE shocks on exchange rates

In this section we first present the first-stage regression results, documenting that ECB and Federal Reserve QE announcements have substantial predictive power for the relative central bank balance sheet. We then present our estimates of the responses of the US dollar-euro exchange rate and their drivers to relative ECB-Federal Reserve QE shocks, obtained from the two-stage least squares local projection regressions described above.

4.1. First-stage results: Predictive content of QE announcements for the relative central bank balance sheet

Column (1) in Table A.3 reports the results for the first-stage regression of Equation (20) with $M = 9$, showing that ECB and Federal Reserve QE announcements in period t predict future changes in their relative balance sheet. Specifically, following a QE announcement by the ECB, its balance sheet expanded statistically significantly relative to that of the Federal Reserve by 19.2 percentage points over the following nine months, i.e. around two percentage points per month. To put this number in perspective, on average over our sample period a two percentage-point expansion of the ECB's balance sheet relative to that of the Federal Reserve amounted to an expansion by roughly 60 bil.

EUR, equivalent to the initial monthly asset purchases under the ECB's APP program launched at the end of 2014.[16] Analogously, following a QE announcement by the Federal Reserve, its balance sheet expanded statistically significantly by 19.8 percentage points relative to that of the ECB. The results reported in Table A.3 also document that the null of instrument validity in the Hansen J-test cannot be rejected, and that the null of under-identification in the Kleibergen and Paap (2006) test is rejected. Moreover, the first-stage regression results are associated with an effective F-statistic that is larger than the relevant 5% critical value, suggesting that the QE announcements are unlikely to be weak instruments.[17] Finally, the results in columns (2) and (3) in Table A.3 suggest that the first-stage regression results are very similar when we consider $M = 6$ or $M = 12$.

4.2. Second-stage results: Dynamic effects of QE shocks

We now turn to the dynamic responses of the bilateral US dollar-euro exchange rate and the generalized UIP components. All impulse response estimates are depicted with 90% confidence bands. Notice that the structure of the error term in the second-stage regression in Equation (16) implies serial correlation of order $max(M, h-1)$. We consider confidence bands based on the fixed-b heteroskedasticity-autocorrelation (HAC) robust standard errors introduced by Kiefer and Vogelsang (2005).[18]

4.2.1. US dollar-euro exchange rate response

The left-hand side panel of Figure B.2 presents the impulse response of the nominal US dollar-euro exchange rate to a relative QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve by one percentage point over the follow-

[16] The ECB balance sheet averaged 2.830 tn. EUR over the sample period we consider. The implied increase of the ECB balance sheet in case of an increase in the balance sheet growth rate differential by two percentage points hence amounts to 56.6 bil. EUR.

[17] As suggested by Montiel Olea and Pflueger (2013) and as in Ramey and Zubairy (2018) 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.

[18] Under fixed-b HAC robust standard errors the bandwidth of the covariance matrix estimator is modeled as a fixed proportion of the sample size. This contrasts with the traditional Newey-West HAC standard errors, where the bandwidth increases more slowly than the sample size and where the asymptotic distributions of HAC robust tests do not depend on the bandwidth or kernel. Kiefer and Vogelsang (2005) document that in finite samples standard errors based on fixed-b asymptotics are more accurate than those based on traditional asymptotics. In our estimations it turns out that confidence bands based on traditional Newey-West HAC standard errors are somewhat tighter, especially at longer horizons h.

ing nine months (see the web appendix for the corresponding estimates of the impulse responses of the nominal bilateral exchange rate for $M = 6$ or $M = 12$). The euro immediately depreciates against the dollar, bottoming at around 0.35% below baseline after nine months. The depreciation is quite persistent and statistically significant up to 18 months. The right-hand side panel of Figure B.2 presents the impulse response of the real US dollar-euro exchange rate, which is very similar to that of the nominal exchange rate, but less persistent and not statistically significant anymore already after 15 months. Our estimates imply substantial effects of QE policies on the US dollar-euro exchange rate. For example, our results suggest that a typical expansionary QE announcement in our sample was followed by an increase in the relative balance sheet of about 20% and, in turn, by a persistent exchange rate depreciation of around 7%.

These estimates are at the upper end of the range of those in the literature, even if it should be noted that these are not perfectly comparable due to different sample periods, QE measures considered and empirical methodologies. On the one hand, Swanson (2017) estimates that Federal Reserve large-scale asset purchases (LSAPs) of 225 bil. USD (i.e. a 7% increase of the balance sheet) depreciated the US dollar-euro exchange rate by 0.2% on the day of the announcement. On the other hand, Weale and Wieladek (2015) estimate that LSAPs of 150 bil. USD (i.e. a 4.5% increase of the balance sheet) depreciated the US dollar-pound exchange rate by about 0.8% after a few months. And according to Wieladek and Garcia Pascual (2016) ECB purchases of 100 bil. EUR (i.e. a 4% increase of the balance sheet) depreciated the effective euro exchange rate by about 0.4% after a few months.[19] In other words, Weale and Wieladek (2015) find a depreciation of the US dollar of around 0.18% after a few months in response to a 1% expansion of the Federal Reserve balance sheet, and Wieladek and Garcia Pascual (2016) find a depreciation of the euro of around 0.1% after a few months in response to a 1% expansion of the ECB balance sheet.

[19] See Weale and Wieladek (2015, p. 23; average over rows 1-6; results reported as responses to a 1% rise in the balance sheet relative to 2009 GDP; US annual GDP was about 15 tn. USD in 2009); and Wieladek and Garcia Pascual (2016, p. 16; average over rows 1-4; results reported as responses to a 1% rise in the balance sheet relative to 2014 GDP; euro area annual GDP was about 10 tn. EUR in 2014).

4.2.2. Decomposition of the exchange rate response

As discussed in Section 2, in order to decompose the response of the exchange rate to QE shocks into the contributions accounted for by generalized UIP components, we also estimate the dynamic responses of the euro-dollar interest rate differentials and the CIP deviation. Impulse responses are obtained from two-stage least squares estimations analogous to that for the exchange rate.

Interest rate differential. The left-hand side panel in the top row of Figure B.3 shows that the three-month euro-dollar money market rate differential declines in response to a relative ECB-Federal Reserve QE shock. The decline in the short-term money-market rate differential is statistically significant after five months, and bottoms at around 1.25 basis points after 12 months.[20] The decline is very persistent, and statistically significant beyond 18 months. These results suggest that a typical expansionary QE announcement in our sample followed by an increase in the relative balance sheet of about 20% caused a persistent decline in the three-month euro-dollar money market rate differential by around 25 basis points. The top right-hand side panel depicts the dynamic response of the policy rate differential. While the impact response is by assumption restricted to be zero, for up to at least five months after the QE shock point estimates of the policy rate differential are slightly positive and statistically significant. Subsequently, point estimates drop, becoming negative after nine months, but also very imprecise with large confidence bands. This evidence suggests that we are not confounding the effects of QE shocks with those of conventional monetary policy shocks that may have occurred in the wake of QE announcements. This is an important finding, as the ECB lowered its policy rates several times during our sample period. In particular, the ECB's DFR (MRO rate) was lowered from 2% (2.5%) to -0.4% (0%) between January 2009 and March 2016, including a few instances in which ECB QE measures were announced alongside policy rate changes.

Our findings for the responses of interest rate differentials provide some indications

[20] One may wonder how policy rates could fall in response to QE shocks in the medium term, given that the ECB and the Federal Reserve were at their effective lower bounds for a considerable part of the time period we consider. However, notice that our estimates are average effects over the sample period, and that neither the ECB nor the Federal Reserve were at their effective lower bounds over the entire sample period.

regarding the transmission channels through which QE measures impact the exchange rate. In particular, notice that according to standard asset pricing theory, at every point in time the three-month rate differential should closely reflect expectations of the policy rate differential over the subsequent three months. Hence, for several months after the shock the point estimates of the response of the three-month differential fall by more than what would be implied by the point estimates of the response of the policy rate. A plausible explanation for the fall in the money-market rate differential, at least in the short term, is the impact of QE on frictions in money markets (Garcia-de-Andoain et al., 2016). The increased liquidity offered by the ECB or the Federal Reserve, especially when the demand for central bank reserves is not fully satiated, can compress liquidity premia of money-market rates, for example by reducing the balance sheet costs of banks (see Martin et al., 2013). A related possible explanation for the decline in money-market rate differentials in the absence of a corresponding decline in (future) policy rate differentials relates to the "flow effects" of QE, under which asset purchases reduce interest rates in particular during periods of market stress when they are actually carried out (see D'Amico and King, 2013).

To the extent that the estimated persistent decline of the three-month differential is consistent with the point estimates of the policy rate differential at longer horizons, it would lend some support to the hypothesis that QE shocks also convey signals about a future accommodation in the relative monetary policy stance. Beyond the impulse response of the policy rate differential, the hypothesis of the signalling channel of QE in the case of the exchange rate is also consistent with the remaining sizable expected depreciation of the euro vis-à-vis the US dollar over one year and a half after the shock. This expected depreciation is consistent with QE measures having credibly signalled to market participants central banks' intentions to keep their policy rate (differential) low for an extended period beyond the 18-months horizon considered in our estimations, possibly even after other central banks would start to raise their rates (which would also contribute to lower the expected interest rate differential).

To further investigate the relevance of the signalling channel, we examine two additional pieces of evidence. First, the bottom left-hand side panel of Figure B.3 shows the response of the two-year sovereign yield differential, and the bottom right-hand side panel the response of the corresponding expectations component.[21] In response to the relative ECB-Federal Reserve QE shock, the two-year sovereign yield differential declines persistently and statistically significantly by over one basis point, driven at least in part by a similar response of the expectations component, which reflects expected future short-term and hence policy rates over the next 24 months (and whose marginal statistical significance may in part reflect some measurement error). Therefore, estimates are consistent with expectations of lower rates over the next two years, up to nine months after a relative QE shock has materialized.

Second, in addition to interest rates we also estimate the effects of a QE shock on markets' expectations about the time until central banks will normalize monetary policy rates. To do so, we consider data on "time-to-lift-off" defined as the number of months until the policy rate is expected to be raised by ten basis points[22], conditional on being at the effective lower bound.[23] The estimates presented in Figure B.4 suggest that ECB QE shocks shifted markets' expectations regarding monetary policy normalisation farther into the future, with a one percentage point increase in the relative balance sheet persistently raising lift-off expectations by around half a month. Specifically, the results suggest that a 20 percentage point increase in the ECB's balance sheet relative to that of the Federal Reserve over nine months, caused by the typical QE announcement, shifted markets' expectations for monetary policy normalisation in the euro area by almost one year into the future (20pp $\times$0.5 months/pp = 10 months). In contrast to the ECB, for the Federal Reserve the effects of QE shocks on "time-to-lift-off " are overall much smaller and generally not statistically significant. Interestingly, these findings are consistent with differences in

[21]The two-year rate expectations components are obtained from the term-structure models of Joslin et al. (2011) for the euro area and Adrian et al. (2013) for the US.

[22]The data for "time-to-lift-off" are constructed using the EONIA forward and the Federal Funds futures curves. We assume that the effective lower bound is at -0.4% for the ECB and at 0% for the Federal Reserve. At every point in time t, the "time-to-lift-off" is determined as the distance to the future date at which the forward curve reaches -0.3% for the ECB and 0.1% for the Federal Reserve.

[23]We set to zero the value of "time-to-lift-off" for the time periods in which the ECB or the Federal Reserve were not at their effective lower bounds. Ideally, we would estimate the regression only for the time period in which the ECB and the Federal Reserve were at their respective effective lower bounds. However, the resulting sample especially in case of the ECB is too short to obtain meaningful estimates. A caveat is thus that these zeros potentially introduce bias in our least squares estimates.

the communication of monetary policy between the ECB and the Federal Reserve. In particular, ECB communication emphasized that policy rates would remain unchanged well past the end of purchases under the APP, thereby directly linking lift-off expectations to the horizon of asset purchases. In contrast, the Federal Reserve placed more emphasis on the dependence of the path of monetary policy on the evolution of macroeconomic data. Overall, we interpret this evidence as suggesting that especially ECB QE shocks have impacted the exchange rate at least in part by signalling an accommodative monetary policy stance in the future.

CIP deviations. Recall the definition of the CIP deviation in (2)

$$\lambda_t = r_t^{€} - \left(r_t^{\$} - f_{t,t+1} + s_t\right), \tag{21}$$

which coincides with that of the dollar cross-currency basis (but for having the opposite sign, (Du et al., 2018)). According to 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 synthetic dollar rate that is larger 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 dollar price in the forward market relative to the spot foreign exchange market than what CIP would imply. Figure B.5 shows that CIP deviations widen by up to around half of a basis point for around nine months in response to the relative QE shock. Namely, the spot dollar relative to the forward dollar exchange rate *appreciates* by slightly more than what is implied by the *fall* in the euro-dollar interest rate differential. The rationale for relative ECB QE shocks widening the CIP deviation — or rendering more negative the cross-currency basis — may relate to an asymmetry between the demand and supply for foreign exchange swap contracts for high and low-yielding currencies. In particular, lower funding costs in the euro area caused by ECB QE shocks would attract foreign borrowers, who desire to hedge their euro exposure and would thereby increase the demand for swap contracts. Against the background of borrowing constraints or other frictions limiting the supply of such contracts and arbitrage opportunities, foreign borrowers would accept a lower price for one euro in terms of US dollars in the forward market — i.e. a lower value of $f_{t,t+1}$ for a given s_t — than what CIP would imply.

Contributions of generalized UIP components to the exchange rate response. Finally, we decompose the response of the exchange rate to QE shocks as outlined in Equation (F.12) into the contributions accounted for by the response of the euro-dollar three-month money market rate differential as well as the CIP deviation. Because we are using three-month interest rates and CIP deviations due to data availability restrictions, we need to consider a modified version of Equation (F.12), obtained by iterating forward the following generalized UIP condition

$$s_t = dr_{t,3} - \lambda_{t,3} + \pi_{t,3} + E_t s_{t+3}, \tag{22}$$

where $dr_{t,3}$ is the three-month interest rate differential, $\lambda_{t,3}$ is three-month CIP deviations and $\pi_{t,3}$ is the corresponding "residual" currency risk premium. The latter's contribution is obtained as a residual, taking as given the estimates of the responses of the interest rate differential, the CIP deviation and the expected exchange rate at the terminal horizon T.[24] Thus, this term effectively captures all deviations from interest rate parity, not just compensation for currency risk.

Figure B.6 presents the decomposition based on point estimates (a very similar decomposition based only on those estimates that are statistically significant at the 90% significance level is shown in the web appendix). While CIP deviations do not contribute much to the effects of QE on the exchange rate, falling current and expected future interest rate differentials underpin the depreciation of the euro vis-à-vis the US dollar in response to the relative QE shock. Residual currency risk premia play a sizable role, in particular in accounting for the trough in the exchange rate depreciation between six and twelve months. For longer horizons, the bulk of the exchange rate response mechanically reflects the estimated terminal depreciation, $E_t s_T$. The substantial role of risk premia in the dynamics of exchange rates echoes the evidence in Engel and West (2010) as well as Engel (2016), who find that a large share of the variation in the dollar exchange rate is attributable to this residual risk premium component. In turn, QE policies can have

[24]The terminal date T of expectations of $E_h s_T$ is different for horizons $h = 0, 3, 6, \dots, 18$, horizons $h = 1, 4, 7, \dots, 17$; and horizons $h = 2, 5, 8, \dots, 16$. Nevertheless, point estimates for these terminal dates are very similar, as shown in Figure B.2.

large effects on currency premia in the models in Gourinchas et al. (2019) and Greenwood et al. (2019).

5. Robustness

We consider several robustness checks that — due to space constraints — we relegate to Section B in the web appendix. In short, we explore whether our findings change when we (i) run separate estimations with ECB and Federal Reserve announcements as instruments; (ii) run the estimations using weekly rather than monthly data; (iii) consider the original announcement dates of Rogers et al. (2014), still excluding "Operation Twist"; (iv) weigh QE announcement dummies based on daily changes in stock prices or long-term bond yields (as we explain in the web appendix this refinement of our approach would allow us to distinguish between central bank information shocks and expansionary QE shocks as well as between expected and unexpected QE shocks, and attribute greater importance to QE shocks that were related to measures that were larger in terms of size and scope); (v) include additional controls (such as the differentials in industrial production growth and CPI inflation as well as leads of QE announcements); and (vi) generalize the definition of QE shocks (by allowing for discounting of future expected shocks in Equation (12)) and the law of motion of the relative balance sheet (by departing from the assumption of a random walk in Equation (13). The key take away from this battery of robustness checks is that our findings for the exchange rate effects of expansionary QE shocks are quite robust.[25]

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

[25]In Section C in the web appendix we consider an extension of our analysis to ECB and Federal Reserve tapering announcements, building on and extending the announcements of Glick and Leduc (2018) as well as Hattori et al. (2016). We find that tapering announcements have little forecasting power for the relative central bank balance sheet in our sample. Most likely, this is because the balance sheet of the Federal Reserve has started to shrink only very recently, several years after tapering was announced; for the ECB the balance sheet has only stabilised but not declined yet, although the first tapering announcement occurred already in March 2018.

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 and the calibration of structural models. This paper addresses this gap in the literature. We do so 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 the relative central bank balance sheet that proxy unobserved QE shocks. Deriving the local projection regression 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 inference, the choice of control variables and their timing. We also pay great attention to model specification tests, including on instrument validity and power, and conduct extensive robustness checks on our baseline specification. We find that QE measures have large and persistent effects on the exchange rate, and that they materialize through a change in interest rate differentials, partly reflecting expectations of the future monetary policy stance, consistent with a significant role of the signalling channel of QE. Nevertheless, our results suggest that a sizable quantitative contribution results also from persistent effects of QE on residual risk premia in foreign exchange markets, which reflect all unexplained deviations from standard interest rate parity.

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Appendix A. Tables

Table A.1: ECB QE announcements

Date	Announcement	Stock market response (in %)	Bond market maresponserket (in b.p.)
08/04/2011	SLTROs and other measures	-3.7	-10
10/06/2011	12/13-month SLTROs	3.1	10
12/08/2011	36-month VLTROs	-2.4	-10
06/05/2014	TLTROs	0.8	-2
09/04/2014	ABSPP and CBPP3 announcement	1.5	2
10/02/2014	ABSPP and CBPP3 details	-2.6	1
01/22/2015	APP announcement	1.6	-8
03/05/2015	APP details	1.0	-4
09/03/2015	Increase of PSPP issue limit	2.2	-7
03/10/2016	CSPP announcement	-1.4	7
04/21/2016	CSPP details	-0.1	6
06/02/2016	CSPP Implementation details	0.0	-3
12/08/2016	Extension of APP	1.3	3
10/26/2017	Extension of APP	1.3	-6

Note: The stock (bond) market response is the one-day change of the Eurostoxx 300 (10-year Bund rate) on the day of the announcements. LTRO refers to Longer-term Refinancing Operations, SLTRO to Supplementary Longer-term Refinancing Operations, VLTRO to Very-long-term Refinancing Operations, TLTRO to Targeted Longer-term Refinancing Operations, ABSPP to Asset-backed Securities Purchase Programme, CBPP3 to Third Covered Bond Purchase Programme, APP to Asset Purchase Programme, PSPP to Public Sector Purchase Programme, and CSPP to Corporate Sector Purchase Programme.

Table A.2: Federal Reserve QE announcements

Date	Announcement	Stock market response (in %)	Bond market response (in b.p.)
11/25/2008	LSAPs announced	0.6	-24
12/01/2008	Bernanke's suggestion to extend QE to Treasuries	-9.4	-21
12/16/2008	FOMC's suggestion to extend QE to Treasuries	5.0	-16
01/28/2009	Fed stands ready to expand QE and buy Treasuries	3.3	12
03/18/2009	LSAPs expanded	2.1	-51
08/27/2010	Bernanke suggests role for additional QE	1.6	16
09/21/2010	FOMC emphasises low inflation	0.4	3
10/12/2010*	FOMC 'sense' additional accommodation appropriate	0.2	7
10/15/2010	Bernanke reiterates Fed stands ready to ease	0.4	4
11/03/2010*	QE2 announced: Fed purchases $600bn Treasuries	-3.0	-7
08/26/2011	Bernanke Speech at Jackson Hole	1.5	-4
08/22/2012*	FOMC judge additional accommodation likely	.02	-9
09/13/2012	QE3 announced: Fed purchases $40bn MBS per month	1.6	-2
12/12/2012*	QE3 expanded	1.6	-2

Note: Dates marked with asterisk are not included in Rogers et al. (2014). MBS stands for mortgage-backed securities. The stock (bond) market response is the one-day change of the S&P 500 (10-year US Treasury rate) on the day of the announcements.

Table A.3: First-stage regression results

	(1) Base ($M = 9$)	(2) $M = 6$	(3) $M = 12$
ECB QE announcement	0.192***	0.138***	0.234***
	(5.88)	(6.18)	(5.58)
Fed QE announcement	-0.198***	-0.142***	-0.195***
	(-4.07)	(-4.23)	(-2.92)
Observations	117	120	114
Hansen-J (p-value)	0.73	0.75	0.51
Kleibergen-Paap-Test (p-value)	0.00	0.00	0.00
F-Stat (1st-stage)	28.60	31.63	20.23
Effective F-statistic	24.02	26.24	17.15
5% crit. value	8.65	9.74	8.70
10% crit. value	7.12	8.10	7.15
R-squared	0.65	0.65	0.62

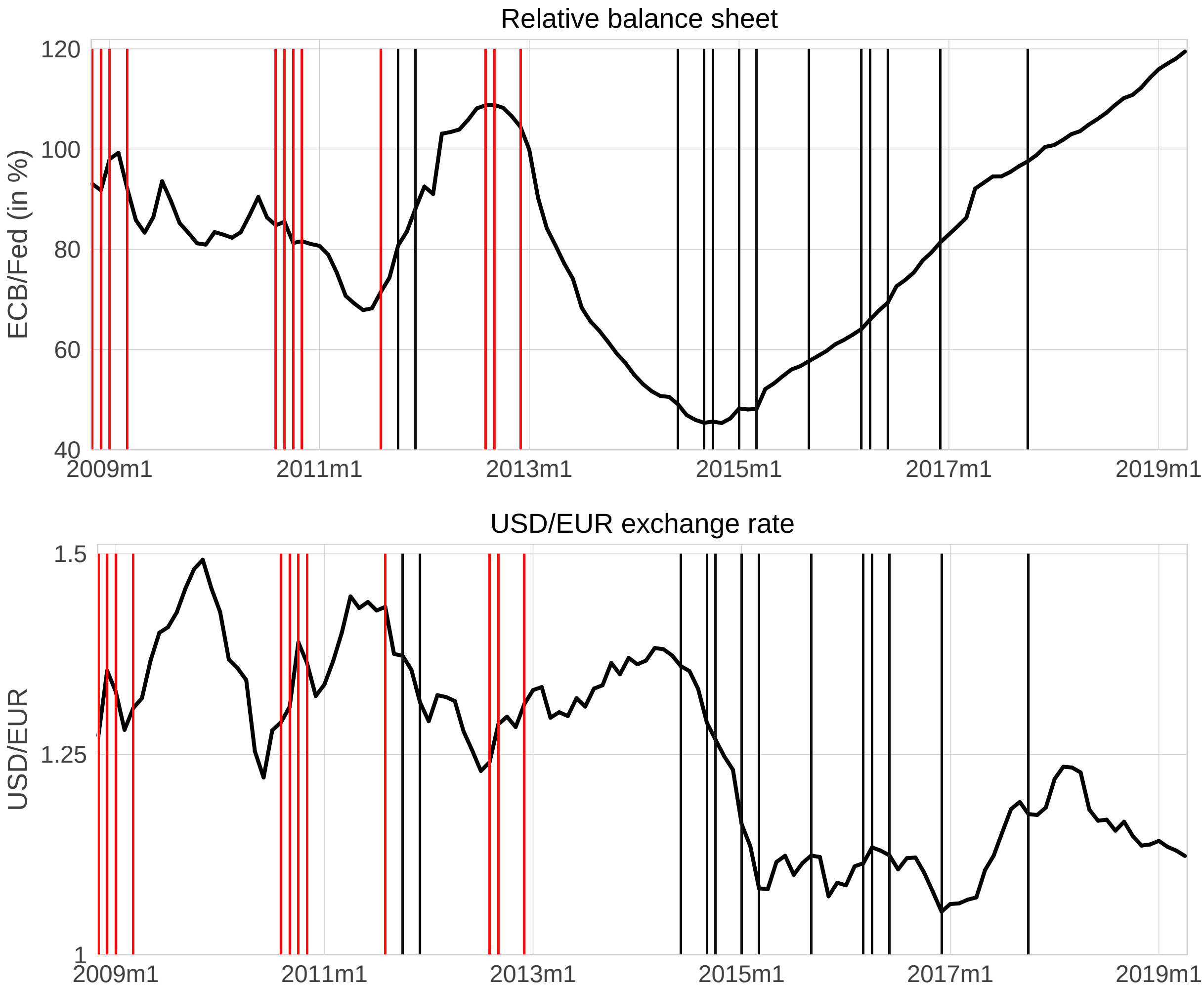
t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

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

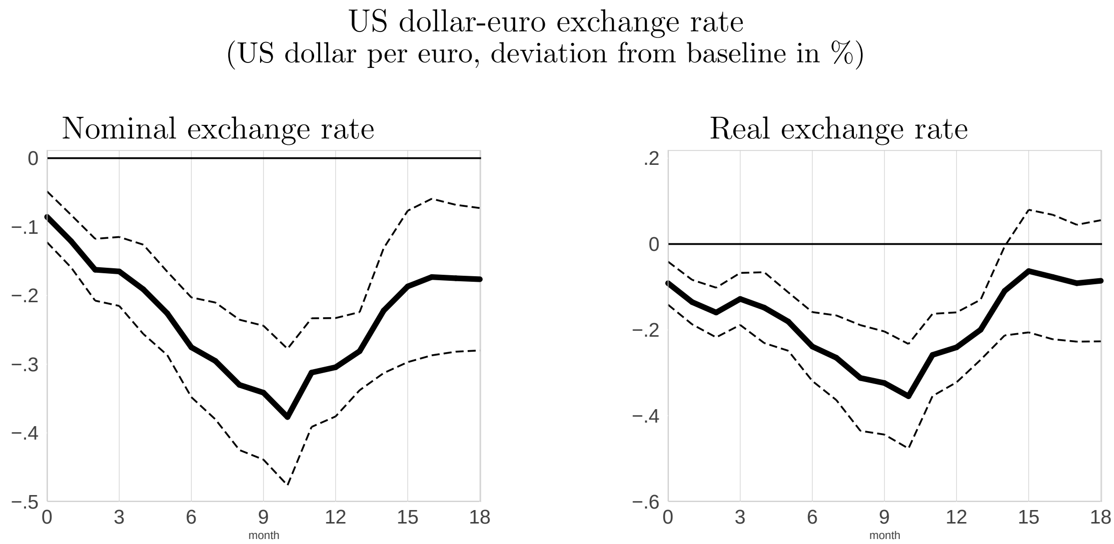
Appendix B. Figures

Figure B.1: Relative balance sheet, the dollar-euro exchange rate and QE announcements



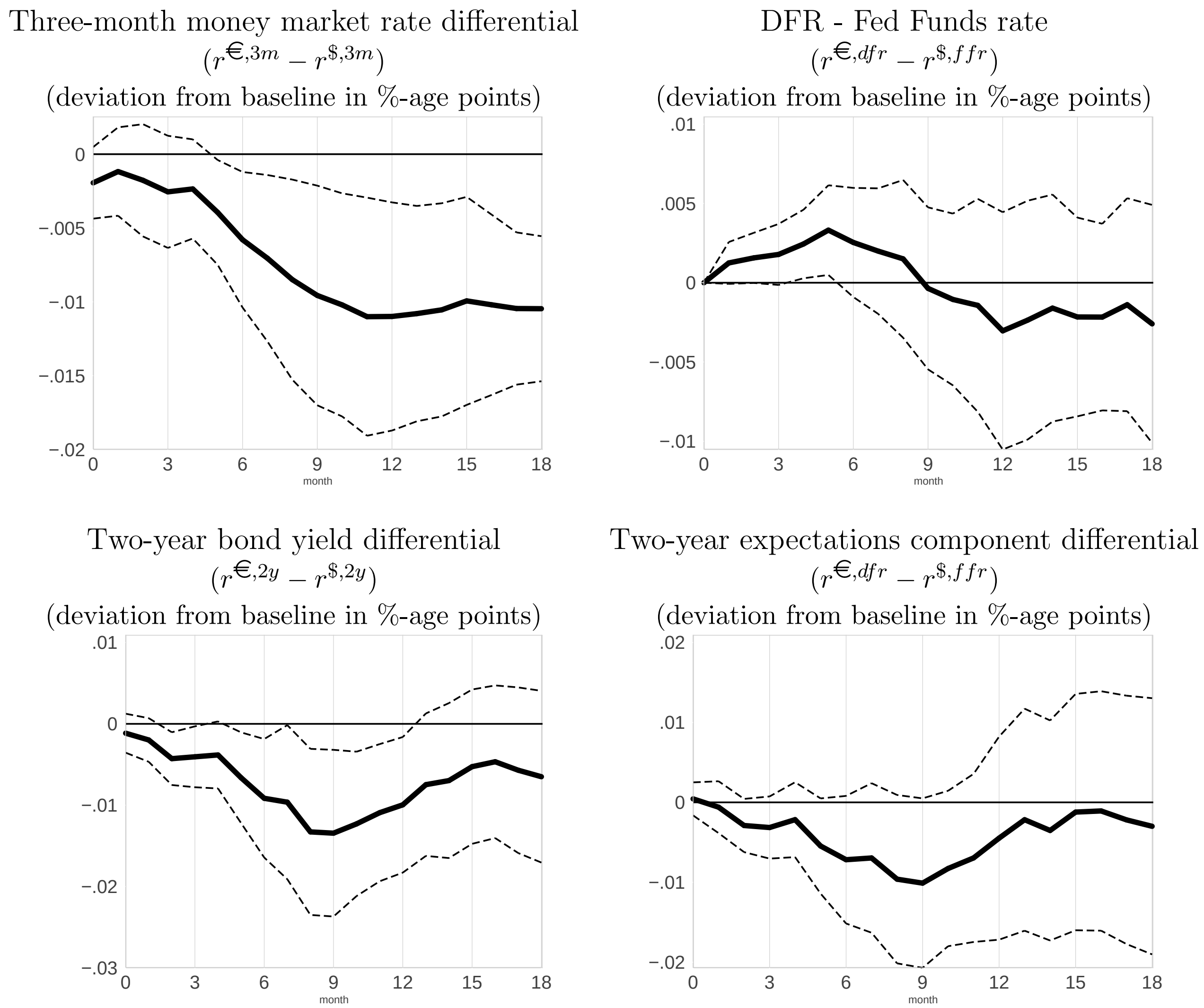
Notes: The upper panel shows the evolution of the relative balance sheet of the ECB and the Federal Reserve (ECB/Fed in percent). The bottom panel plots the USD/EUR exchange rate. Across both charts, the black (red) vertical lines indicate the dates of QE announcements by the ECB (Federal Reserve).

Figure B.2: Exchange rate response to a relative ECB-Federal Reserve QE shock



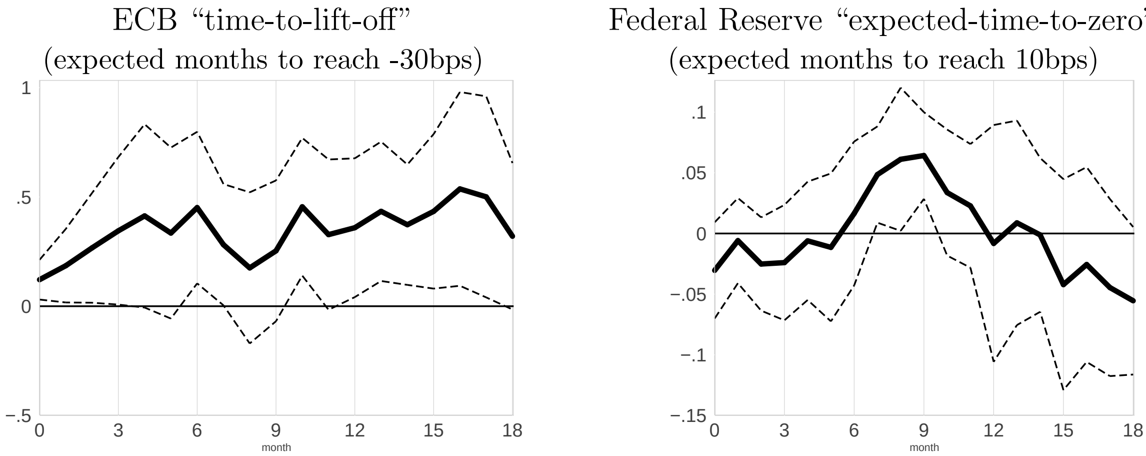
Note: The figure presents the estimates of the response of the US dollar-euro nominal bilateral exchange rate to the relative QE shock that expands the ECB balance sheet relative to that of the Federal Reserve. The estimates are obtained from the two-stage least squares local projection regression in Equations (15) and (20). The dashed lines represent 90% confidence bands based on the fixed-b heteroskedasticity-autocorrelation (HAC) robust standard errors introduced by Kiefer and Vogelsang (2005).

Figure B.3: Impulse responses of interest rate differential to a relative ECB-Federal Reserve QE shock



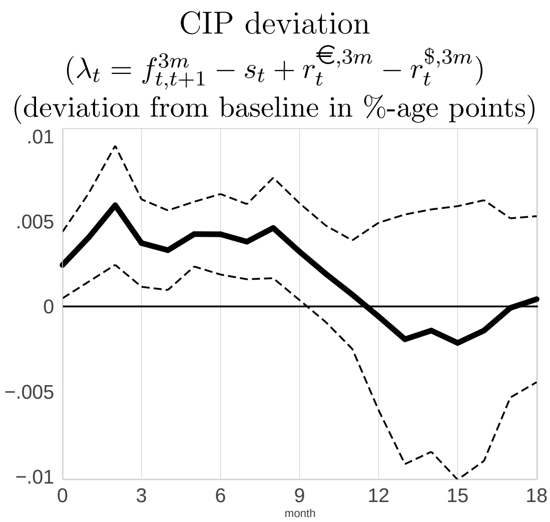
Note: See the note to Figure B.2.

Figure B.4: Time-to-lift-off responses to a relative ECB-Federal Reserve QE shock



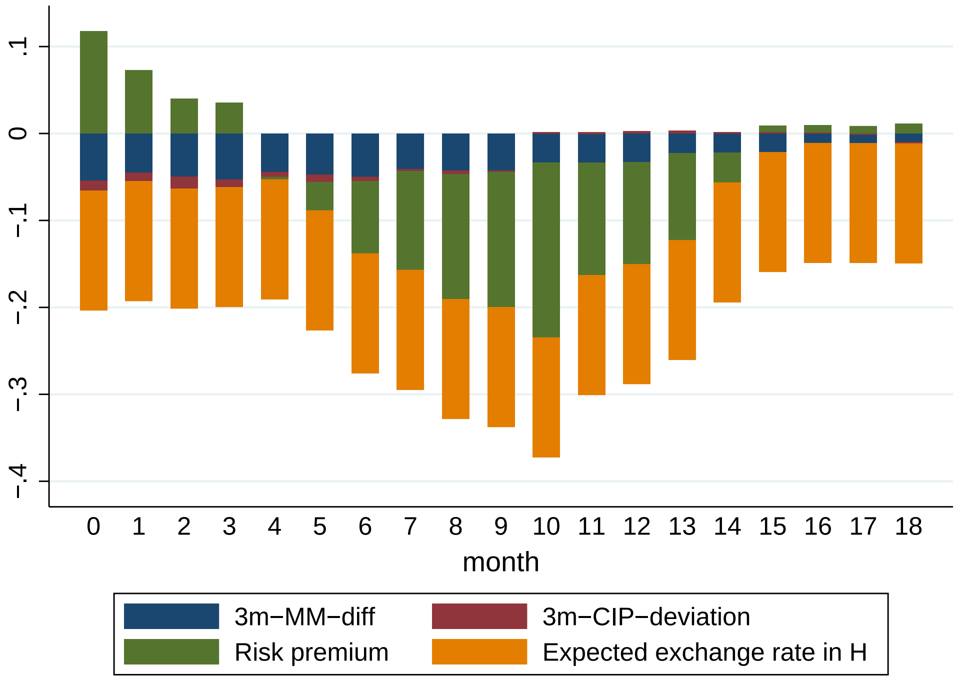
Notes: The figure presents the responses of "time-to-lift-off" for the ECB and the Federal Reserve to a relative QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve by one percentage point. See also the note to Figure B.2.

Figure B.5: Impulse responses of the CIP deviation to a relative ECB-Federal Reserve QE shock



Note: See the note to Figure B.2.

Figure B.6: Decomposition of exchange rate response to a relative ECB-Federal Reserve 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 (F.12).

Appendix C. Web appendix — Additional results

Figure H.7 depicts the impulse responses of the exchange rate and the short-term interest rate differential for the alternative choices $M = 6$ and $M = 12$. Figure H.8 presents the decomposition of the exchange rate response into the contributions of the UIP fundamentals when dropping those estimates that are not statistically significant at the 90% level.

Appendix D. Web appendix — Robustness checks

In this section we present the robustness checks mentioned in the paper. Specifically, we explore whether our findings change when we (i) run separate estimations with ECB and Federal Reserve announcements as instruments; (ii) run the estimations using weekly rather than monthly data; (iii) weigh QE announcement dummies with daily changes in stock prices or long-term bond yields in order to distinguish between central bank information and expansionary QE shocks as well as between expected and unexpected QE shocks, and in order to attribute greater importance to QE shocks that were related to measures that were larger in terms of size and scope; (iv) consider the original announcement dates of Rogers et al. (2014), still excluding "Operation Twist"; (v) include the differentials in industrial production growth and CPI inflation as well as leads of the QE announcements as additional controls; and (vi) generalize the definitions of QE shocks by allowing for discounting of future expected shocks in Equation (12) in the paper and the law of motion of the relative central bank balance sheet by departing from the assumption of a random walk in Equation (13) in the paper. The results of the corresponding first-stage regressions are reported in Table G.6, and the estimated impulse responses of the euro-dollar exchange rate and the short-term interest rate differential are depicted in Figures H.9 to H.14.

Appendix D.1. Using only ECB or Federal Reserve QE announcements

Columns (1) and (2) in Table G.6 report the first-stage regression results for specifications in which we use either ECB or Federal Reserve QE announcements as instruments. Analogously, Figure H.9 presents the estimates of the responses of the exchange rate and the short-term interest rate differential to a QE shock that raises the ECB's balance sheet relative to that of the Federal Reserve, instrumented by either the ECB or the Federal Reserve announcement dummies. The estimates of the impulse responses are similar, suggesting that the exchange rate is impacted similarly by ECB and Federal Reserve QE shocks to the relative balance sheet. If anything, point estimates of the response of the exchange rate are smaller when using Federal Reserve QE announcements as instruments only — where for comparability we have kept the sign of the response the same as that to the ECB shock. However, not only are the standard errors larger, but the effective F-statistics reported in column (2) in Table G.6 is below the relevant critical values, implying that using only Federal Reserve QE announcements might give rise to weak instrument problems, which would further increase estimation uncertainty.

Appendix D.2. Weekly data

Recall that in our baseline specification data frequency is monthly. We do not use weekly data in our baseline even if this would allow us to more accurately assign QE announcements to the respective time periods because weekly data are considerably more noisy. Column (3) in Table G.6 reports the first-stage regression results for the specification with weekly data and Figure H.10 presents the corresponding impulse responses. Analogous to the baseline specification, in the first-stage regression the dependent variable is the growth rate differential between the central banks' balance sheets between weeks $t-1$ and $t+36$. The results for both the first-stage regressions and the impulse responses are again very similar to those of the baseline; the response of the interest rate differential is initially weaker and not statistically significant in the first four months. As expected, the R-squared of the first-stage regression is lower.

Appendix D.3. Weighting and alternative selection of QE announcements

There are several possible concerns with our choice of QE announcements and the use of announcement dummies. First, it could be that the QE measures underlying the announcements we consider are all different in magnitude; this issue relates to the notion that one would ideally use announcement dummies weighted by the announced amounts of asset purchases, as discussed already in Section 3.2 in the paper. Not doing so in general implies a reduction of the power of the QE announcements we consider as instruments. Second, it could be that some of the QE measures we consider were expected by markets. In this case, even if the QE measures were announced in period t, one should conceive them as QE shocks in earlier periods $\eta_{t+m|t-s}$, $s > 0$. From an econometric point of view, this concern implies a violation of the assumption that $Cov(\eta_{t+m|t-s}, a_t^j) = 0$ for $s > 0$, which is required for instrument validity (see Equations (15) and (16) in the paper). And finally, it could be that rather than being perceived as expansionary QE shocks, some measures might have been perceived by market participants as a revelation of private information of the central bank about adverse demand or financial shocks (see Campbell et al., 2017; Miranda-Agrippino and Ricco, 2017; Nakamura and Steinsson, 2018). In this case, even if the QE measures were unexpected in period t, one should conceive them as central bank information shocks, i.e. non-QE structural shocks $\boldsymbol{e}_t$. This concern undermines the plausibility of the assumption that $Cov(\boldsymbol{e}_t, a_t^j) = 0$, which is also required for instrument validity (see Equations (15) and (16) in the paper).

Addressing these concerns requires identifying those QE announcements which were unexpected, not a revelation of private information of the central bank about adverse shocks, and to weigh the announcements according to the size of the underlying QE measures. In an attempt to address these concerns, we borrow from the literature on high-frequency identification of monetary policy shocks (Gürkaynak et al., 2005). More specifically, building on Jarocinski and Karadi (2019), instead of Equation (17) in the paper we assume the following relation between unobserved QE shocks and announcements

$$\eta_{t+m|t} = \sigma_m + \mu_m^{\text{ECB}} \cdot \left[a_t^{\text{ECB}} \times \Delta e_t^{€} \times I(\Delta e_t^{€} > 0)\right] + \mu_m^{\text{Fed}} \cdot \left[a_t^{\text{Fed}} \times \Delta e_t^{\$} \times I(\Delta e_t^{\$} > 0)\right] + u_{t,m}, \tag{D.1}$$

where $\Delta e_t^{€}$ and $\Delta e_t^{\$}$ represent the changes in euro area and US stock prices on the day of QE announcements, and $I(\Delta e_t^{€} > 0)$ and $I(\Delta e_t^{\$} > 0)$ are indicator variables which equal unity when the stock price changes are positive and zero otherwise.[26]

The following observations are in order. First, in considering only those QE announce-

[26]For the two months in which we have two Federal Reserve announcements we consider the ones with the larger positive stock price change (or smaller negative bond yield change). Results are broadly insensitive to these choices.

ments which were associated with a positive stock price "surprise" we borrow from the "poor man" identification approach in Jarocinski and Karadi (2019), which these authors show helps distinguishing monetary policy shocks from central bank information shocks. Since we are interested in the effects of expansionary QE shocks followed by increases in central bank balance sheets, it seems plausible to condition only on positive stock price surprises. Indeed a negative stock price surprise brought about by a QE announcement perceived as "bad news" could have ambiguous effects on the exchange rate, i.e. still resulting in a depreciation which, however, would not be due to a QE shock. Second, weighting by the size of the — positive — stock price response helps to attribute a larger impact to QE announcements which surprised the market than announcements that were largely expected. Finally, to the extent that larger or generally more effective QE programs induce larger stock price movements, other things equal, weighting by the size of the stock price response also would help making QE announcements about measures that were perceived to be more effective because of their size (or composition) have a greater impact on our estimates. The third column in Tables 1 and 2 in the paper indicates that there are nine announcements (out of fourteen) for the ECB and twelve (out of fourteen) for the Federal Reserve for which stock prices rose on the day of the QE announcement.

The results for the first-stage regression of the specification in Equation (D.1) are reported in column (4) of Table G.6, and the impulse responses in the top panels in Figure H.11. The first-stage results are very similar to those from our baseline, even though the effective F-statistic drops below the 5% critical value, pointing to a slight loss in instrument power. Notably, the coefficient estimates imply that an ECB QE announcement that was associated with a 1% increase in euro area equity prices on the same day, raised the balance sheet of the ECB by 8.8 percentage points relative to that of the Federal Reserve over the following nine months. The response of the nominal exchange rate to a QE shock which raises the relative balance sheet by one percentage point is also very similar to the baseline, if anything showing a more negative point estimate in the first few months after the shock The response of the three-month interest rate differential is less precisely estimated.

Column (5) of Table G.6 reports results from a first-stage regression with an alternative weighting scheme, namely using the change in bond yields instead of stock prices on the day of QE announcements.[27] In particular, in this specification the indicator variables $I(\cdot)$ equal unity only if changes in ten-year German Bund and US Treasury yields are *negative* on the day of the announcements (see Tables 1 and 2 in the paper, showing that we are left with eight ECB and nine Federal Reserve announcements, respectively). The associated impulse responses are shown in the bottom panels in Figure H.11. Again, impulse responses are consistent with those from our baseline, even though bond yields seems to be weaker instruments than stock prices, according to test statistics in column (5).

Appendix D.4. Alternative announcements

Column (6) in Table G.6 and Figure H.12 present the results for the specification in which we use the Rogers et al. (2014) announcements for the Federal Reserve, still without announcements relating to "Operation Twist". The results are again very similar to those from the baseline.

Appendix D.5. Including additional macro variables and leads of announcements as controls

Stock and Watson (2018) discuss a "lead/lag exogeneity" requirement for consistent estimation with local projections with external instruments. In particular, in general instruments need to be uncorrelated with future and past structural shocks, at least after including control variables. 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. Although 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 our estimation only requires that QE announcements are uncorrelated with contemporaneous and future structural shocks, we explore the robustness of our findings to the inclusion of variables as controls that proxy lagged structural shocks to which the QE announcements might respond to (Jorda et al., 2015; Stock and

[27] We thank Eric Swanson for suggesting this specification.

Watson, 2018). In particular, we include as additional controls the lags of the differential between euro area and US industrial production growth and CPI inflation.

Furthermore, Stock and Watson (2018) suggest that in order to improve efficiency one can include future values of the instruments as controls in the local projection regression. The underlying intuition is that the error term $\zeta_{t,h}$ defined in Equation (16) of the second-stage regression in Equation (15) in the paper includes future QE shocks. Given our identifying assumption reflected in Equation (15) in the paper, these future QE shocks are correlated with future QE announcements a_t^j. Hence, including future QE announcements as controls should reduce the variance of the error term in Equation (16) in the paper, and therefore improve efficiency of estimation. Of course this is not necessarily to be expected to materialise in finite samples.

Column (7) of Table G.6 reports the results for the first-stage regression of the specification with lagged macro variables as additional controls. As the first-stage results (at least for $h = 0$) are identical to those of the baseline specification when leads of QE announcements are added as controls, we do not report them in Table G.6; for higher h, when h leads of the instruments are included as controls, the first-stage regression and test results are similar to the baseline. The corresponding impulse responses presented in Figure H.13 are also very similar to the baseline.

Appendix D.6. Generalizing the law of motion of the relative central bank balance sheet

Recall that in our baseline specification we assume that the relative central bank balance sheet is a random walk process, which implies that shocks have permanent effects. In fact, it seems this is not too implausible an assumption, as with a value of .994 the estimate of the autoregressive coefficient in our data is virtually indistinguishable from unity. Nevertheless, instead of Equation (13) in the paper one could specify

$$BS_t = \delta_0 + \rho BS_{t-1} + \sum_{m=0}^{M} \eta_{t|t-m} + \boldsymbol{\delta}' \boldsymbol{e}_t. \tag{D.2}$$

We can then substitute the anticipated QE shock $\eta_{t+m|t}$ in the local projection of the exchange rate by

$$\eta_{t+m|t} = BS_{t+m} - \rho BS_{t+m-1} - \left(\delta_0 + \sum_{\substack{k=0 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \boldsymbol{e}_{t+m} \right),$$

to obtain

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} BS_{t+m} - \rho BS_{t+m-1} \right) + \omega_{t-1,h} + (M+1)\delta_0 + \zeta_{t,h}.$$

In turn, the first-stage regression is then be given by

$$\sum_{m=0}^{M} BS_{t+m} - \rho BS_{t+m-1} = \varpi + \theta^{\text{ECB}} a_t^{\text{ECB}} + \theta^{\text{Fed}} a_t^{\text{Fed}} + \omega_{t-1,h} + \xi_t. \tag{D.3}$$

While it is not possible to separately estimate ρ and α_h^{qe}, we can explore whether our results are sensitive to plausible values of ρ. The results for the first-stage regression are reported in column (8) in Table G.6 for $\rho = 0.95$ and the impulse responses in Figure H.14. The results are very similar to those of the baseline, despite the fact that $\rho = 0.95$ represents a substantial deviation from the implied value $\rho = 0.994$.[28]

Appendix D.7. Generalizing the definition of the QE shock

Recall that in our baseline in Equation (12) in the paper we assumed that a QE shock is defined as

$$\varepsilon_t^{qe} = \sum_{m=0}^{M} \eta_{t+m|t}. \tag{D.4}$$

We can generalise this and assume

$$\varepsilon_t^{qe} = \sum_{m=0}^{M} \phi_m \eta_{t+m|t} \tag{D.5}$$

[28]Notice that because the variable of interest in the second-stage regression is $\sum_{m=0}^{M} BS_{t+m} - \rho BS_{t+m-1}$ rather than $BS_{t+M} - BS_{t-1}$ as in our baseline, the impulse response cannot be interpreted as the effect of a QE shock that increases the relative balance sheet by one percentage point.

The intuition for this generalisation is that in the context of ECB and Federal Reserve QE it may be plausible to assume that markets discounted expected future asset purchases. This could have been because given the unprecedented scope of QE measures markets were not fully convinced whether the ECB and the Federal Reserve would indeed carry out the measures in the way they were announced. In this case, we would have $\phi_m > \phi_{m+1}$. In order to account for this possibility in our framework while precluding proliferation of parameters, we assume geometric discounting, i.e. $\phi_m = \phi^m$. Under this assumption, the second-stage regression is given by

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} \phi^m \Delta BS_{t+m} \right) + \omega_{t-1,h} + (M+1)\delta_0 + \zeta_{t,h}. \tag{D.6}$$

While it is again not possible to separately estimate ϕ and α_h^{qe}, we can explore whether our results are sensitive to plausible values of ϕ. The results for the first-stage regression of this specification are reported in column (9) of Table G.6 for $\phi = 0.9$, and Figure H.15 presents the corresponding estimates of the impulse responses of the exchange rate to the QE shock. The results are very similar to those from the baseline.[29]

Appendix E. Web appendix — Extension to tapering

We extend our analysis to consider seven Federal Reserve and three ECB tapering announcements – see Tables G.4 and G.5, which also include the changes in equity prices and bond yields on those dates. In more detail, for the baseline specification for the analysis of the exchange rate effects of tapering we do the following. Concerning Federal Reserve tapering, we consider, with a few selected but motivated exceptions, the union of the dates listed in Glick and Leduc (2018) as well as Hattori et al. (2016) as a starting point. The exceptions we drop are the announcements on 19 March 2014 ("Will keep funds rate low for a "considerable time" after asset purchase program ends") and 17 December 2014 ("Will be patient in beginning to normalize policy"), which pertain to interest rate forward guidance rather than tapering. Concerning the ECB tapering, we

[29]Notice again that because the variable of interest in the second-stage regression is $\sum_{m=0}^{M} \phi^m \Delta BS_{t+m}$ rather than $BS_{t+M} - BS_{t-1}$ as in our baseline, the impulse response cannot be interpreted anymore as the effect of a QE shock that increases the relative balance sheet by one percentage point.

consider the following announcements: 8/3/2018, when the Governing Council dropped its easing bias on QE; 26/04/2018, when tapering was discussed during the ECB press conference and 14/06/2018, when the timing and modalities of tapering were announced by the Governing Council.

Analogous to our baseline on expansionary QE, we consider specifications with separate dummies for the ECB and Federal Reserve tapering dates. The results for the first-stage regressions with the different sets of tapering announcements are reported in columns (1) to (3) in Table G.7. The results suggest that the tapering announcements have little forecasting power for the relative central bank balance sheet, as both coefficient estimates are small and not statistically significant; we also fail to reject the null of instrument irrelevance. The Federal Reserve dummy even has the wrong, negative sign. Given these results, it is certainly not informative to consider the impulse responses estimated in the second-stage regressions for these specifications. Columns (4) to (6) document that the results for the first-stage regressions are much better regarding the outcomes for the tests for instrument relevance when including both the tapering announcements and our baseline expansionary announcements. However, it is clear that this is mainly driven by the expansionary announcements. In fact, the coefficient estimates on the tapering announcements continue to be either not statistically significant in case of the ECB or to have the wrong sign in case of the Federal Reserve. Therefore, it would again not be very informative to consider impulse responses to a tapering shock estimated from the second-stage regressions in these specifications.

A possible reason for the lack of forecasting power of the tapering announcements is that even though Federal Reserve tapering was announced more than five years ago, it has resulted in a noticeable decline in its balance sheet only very recently (see Figure H.16). This is in stark contrast to expansionary QE announcements, after which balance sheets rapidly expanded. Technically, the parameter M which we set to nine months in our baseline for the effects of expansionary QE is plausibly much larger in the case of tapering, most likely too large relative to the available sample size. Therefore, our methodology would need a longer sample to produce statistically reliable estimates of the effects of tapering.

Appendix F. Web appendix — Exchange rate determination and CIP deviations

Consider an investor whose relevant nominal discount factor is expressed in US dollars ("American" investor), $\mathcal{D}_t^{\$}$.[30] Under standard conditions, the relation between $\mathcal{D}_t^{\$}$ and the one-period nominally risk-free US dollar nominal interest rate $R_t^{\$}$ is then given by:

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

Equation (F.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:

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

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

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

and

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

When $\lambda_t^{\$} = 0$, Equation (F.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. when the investor is saving. When $\lambda_t^{\$} > 0$, one dollar in period t is worth

[30] 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.

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.[31] The rationale for $\lambda_t^{€}$ is analogous, but refers to borrowing and saving in the synthetic risk-free dollar market at the rate $\frac{F_{t,t+1}R_t^{€}}{S_t}$.

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

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

where $\lambda_t \equiv 1 - \frac{1-\lambda_t^{\$}}{1-\lambda_t^{€}}$ represents CIP deviations.[32] 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 (F.5) yields:

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

where we have assumed that CIP deviations λ_t are small.[33] Notice that our definition of

[31] 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.

[32] 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:

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

[33] 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:

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

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., 2018).

the CIP deviation implied by Equation (F.6), namely

$$\lambda_t \equiv r_t^{€} - \left(r_t^{\$} - f_{t,t+1} + s_t\right), \tag{F.7}$$

coincides with the market definition of the cross-currency basis, except for having the *opposite* sign (see, for example, Du et al., 2018).

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:

$$\frac{E_t\left(\mathcal{D}_{t+1}^{\$}\right) F_{t,t+1}}{S_t} R_t^{€} = \frac{E_t\left(\mathcal{D}_{t+1}^{\$} S_{t+1}\right)}{S_t} R_t^{€}. \tag{F.8}$$

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

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

Assuming log-normality and taking logs yields:

$$\begin{aligned} f_{t,t+1} &= E_t s_{t+1} + Cov_t\left(d_{t+1}^{\$}, s_{t+1}\right) + \frac{1}{2} Var_t\left(s_{t+1}\right) \\ &= E_t s_{t+1} + \pi_t. \end{aligned} \tag{F.10}$$

Taking into account Jensen's inequality (the term $\frac{1}{2}Var_t\left(s_{t+1}\right)$), 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.[34]

By substituting the forward rate in Equation (F.10) in the CIP condition in Equation

[34]Specifically, premium π_t is positive if a 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 negative when dollar depreciation is expected to be associated with a lower discount factor of the investor.

(F.6), we obtain the UIP condition:

$$s_t = E_t s_{t+1} + dr_t - \lambda_t + \pi_t, \tag{F.11}$$

where $dr_t \equiv r_t^{€} - r_t^{\$}$. Iterating forward Equation (F.11) for T periods and applying the law of iterated expectations yields:

$$s_t = E_t s_{t+T} + \sum_{j=0}^{T-1} E_t dr_{t+j} - \sum_{j=0}^{T-1} E_t \lambda_{t+j} + \sum_{j=0}^{T-1} E_t \pi_{t+j}, \tag{F.12}$$

which shows that the spot exchange rate in period t is determined by current and expected future fundamentals — i.e. short-term interest rate differentials, risk premia, CIP deviations, and the expected value of the exchange rate at horizon T.

An interesting question to ask is whether CIP deviations can arise due to counterparty risk. Under the maintained assumption that R_t^E is risk free, a simple way of thinking of counterparty risk in the forward exchange rate market is the following. Rather than at the contracted, known exchange rate $F_{t,t+1}$, the conversion into dollars of the one-period euro payoff R_t^E may be risky if there is a probability that it has to take place on the spot market at the uncertain (risky) exchange rate S_{t+1} because the counterparty cannot deliver dollars anymore. Assuming the (conditional) probability of the latter event is π_t, we have that no-arbitrage under no borrowing constraints implies the following:[35]

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

$$\frac{F_{t,t+1}R_t€}{S_t} > R_t^{\$} \Leftrightarrow \left(E_t\left(S_{t+1}\right) - F_{t,t+1}\right) - Cov_t\left(\mathcal{D}_{t+1}^{\$}, S_{t+1}\right) R_t^{\$} > 0.$$

Thus a sufficient condition for positive CIP deviations ($\frac{F_{t,t+1}R_t€}{S_t} > R_t^{\$}$) is that the expres-

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$$\frac{E_t\left(\mathcal{D}_{t+1}^{\$}\right) F_{t,t+1} + \pi_t\left[E_t\left(\mathcal{D}_{t+1}^{\$}\right)\left(E_t\left(S_{t+1}\right) - F_{t,t+1}\right) - Cov_t\left(\mathcal{D}_{t+1}^{\$}, S_{t+1}\right)\right]}{S_t} R_t€ = E_t\left(\mathcal{D}_{t+1}^{\$}\right) R_t^{\$}$$

$$\frac{F_{t,t+1}R_t€}{S_t}\left[1 + \pi_t \frac{\left(E_t\left(S_{t+1}\right) - F_{t,t+1}\right) - R_t^{\$} Cov_t\left(\mathcal{D}_{t+1}^{\$}, F_{t,t+1}\right)}{F_{t,t+1}}\right] = R_t^{\$}$$

sion $\left(E_t\left(S_{t+1}\right)-F_{t,t+1}\right)-Cov_t\left(\mathcal{D}^{\$}_{t+1},S_{t+1}\right)R^{\$}_t$ is different from zero. However, it can be shown that this expression is always zero, as it corresponds to the expected forward premium. For our investor, it should be the case that the one period risk-adjusted expected return of investing in the dollar euro forward market or in the dollar euro spot market should be the same, namely

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

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

$$F_{t,t+1}=E_t\left(S_{t+1}\right)-\frac{Cov_t\left(\mathcal{D}^{\$}_{t+1},S_{t+1}\right)}{E_t\left(\mathcal{D}^{\$}_{t+1}\right)} \tag{F.13}$$

Notably, these returns are equalized also if they are subject to the same borrowing constraints and transaction costs. But then it is immediate that deviations from CIP cannot arise from counterparty forward market risks that are perfectly correlated with future spot market risks.The same relation for the "European" investor would read

$$F_{t,t+1}=\left[E_t\left(1/S_{t+1}\right)-\frac{Cov_t\left(\mathcal{D}_{t+1}€,1/S_{t+1}\right)}{E_t\left(\mathcal{D}_{t+1}€\right)}\right]^{-1}.$$

Appendix G. Web appendix — Additional tables

Table G.4: ECB QE tapering measures

Date	Announcement	Stock price change (in %)	Bond yield change (in b.p.)
08/03/2018	APP Tapering discussion	0.1	-3
26/04/2018	APP Tapering discussion	0.1	-3
14/06/2018	APP Tapering announcement	1.1	-6

Note: The stock (bond) market response is the one-day change of the Eurostoxx 300 (10-year Bund rate) on the day of the announcements.

Table G.5: Fed QE tapering measures

Date	Announcement	Stock price change (in %)	Bond yield change (in b.p.)
22/05/2013	Fed testimony	-0.8	9
19/06/2013	FOMC meeting	-1.4	13
18/09/2013	FOMC meeting	1.2	-17
18/12/2013	Start of Tapering	1.7	4
29/01/2014	Tapering	-1.0	-8
19/03/2014	Tapering	-0.6	10
30/04/2014	Tapering	0.3	-4
29/10/2014	End QE3	-0.1	4

Note: The stock (bond) market response is the one-day change of the S&P 500 (10-year US Treasury rate) on the day of the announcements.

Table G.6: First-stage regression results for robustness checks

	(1) ECB	(2) Fed	(3) Weekly	(4) Stock	(5) Bond	(6) RSW	(7) Macro	(8) $\rho = .95$	(9) $\phi = .9$
ECB QE announcement	0.218***		0.150***			0.205***	0.162***	0.103***	0.125***
	(6.34)		(6.26)			(6.14)	(4.39)	(3.57)	(6.01)
Fed QE announcement		-0.230***	-0.180***			-0.197***	-0.202***	-0.152***	-0.123***
		(-3.68)	(-3.66)			(-4.11)	(-4.66)	(-3.75)	(-4.19)
ECB announcement - accommodative surprise				8.796**	-2.482***				
				(2.60)	(-5.09)				
Fed announcement - accommodative surprise				-9.328***	0.588*				
				(-3.06)	(1.87)				
Observations	117	117	511	117	117	117	117	117	117
Hansen-J (p-value)	.	.	0.27	0.17	0.33	0.19	0.69	0.78	0.67
Kleibergen-Paap-Test (p-value)	0.00	0.02	0.00	0.01	0.01	0.00	0.00	0.00	0.00
F-Stat (1st-stage)	40.20	13.53	28.04	9.61	15.59	31.19	22.57	18.58	31.48
Effective F-statistic	40.20	13.53	19.35	9.63	8.89	27.31	20.44	13.42	25.71
5% crit. value	23.11	23.11	15.21	11.27	14.84	7.44	7.66	9.78	8.41
10% crit. value	19.75	19.75	12.82	9.64	12.50	6.06	6.28	8.08	6.91
R-squared	0.55	0.53	0.41	0.49	0.46	0.60	0.69	0.76	0.67

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 G.7: First-stage regression results for relative tapering shocks

	(1) Base	(2) Glick and Leduc	(3) Hattori et al.	(4) Base	(5) Glick and Leduc	(6) Hattori et al.
ECB Taper announcement	-0.061	-0.057	-0.067	-0.015	-0.008	-0.018
	(-0.58)	(-0.55)	(-0.63)	(-0.19)	(-0.11)	(-0.23)
Fed Taper announcement	-0.054			-0.094^{+}		
	(-0.61)			(-1.51)		
Fed Taper announcement - Glick		-0.059			-0.146^{**}	
		(-0.46)			(-2.05)	
Fed Taper announcement -Hattori			-0.105			-0.105^{+}
			(-1.26)			(-1.29)
ECB QE announcement				0.188^{***}	0.190^{***}	0.183^{***}
				(5.51)	(5.48)	(5.41)
Fed QE announcement				-0.195^{***}	-0.194^{***}	-0.196^{***}
				(-3.81)	(-3.76)	(-3.81)
Observations	117	117	117	117	117	117
Hansen-J (p-value)	0.42	0.36	0.44	0.71	0.87	0.80
Kleibergen-Paap-Test (p-value)	0.68	0.74	0.42	0.00	0.00	0.00
F-Stat (1st-stage)	0.35	0.27	0.96	13.05	13.28	13.05
Effective F-statistic	0.35	0.23	1.03	10.88	12.18	10.23
5% crit. value	12.28	14.40	5.87	13.60	13.47	13.96
10% crit. value	10.30	12.16	4.69	12.11	12.02	12.39
R-squared	0.40	0.40	0.41	0.66	0.66	0.66

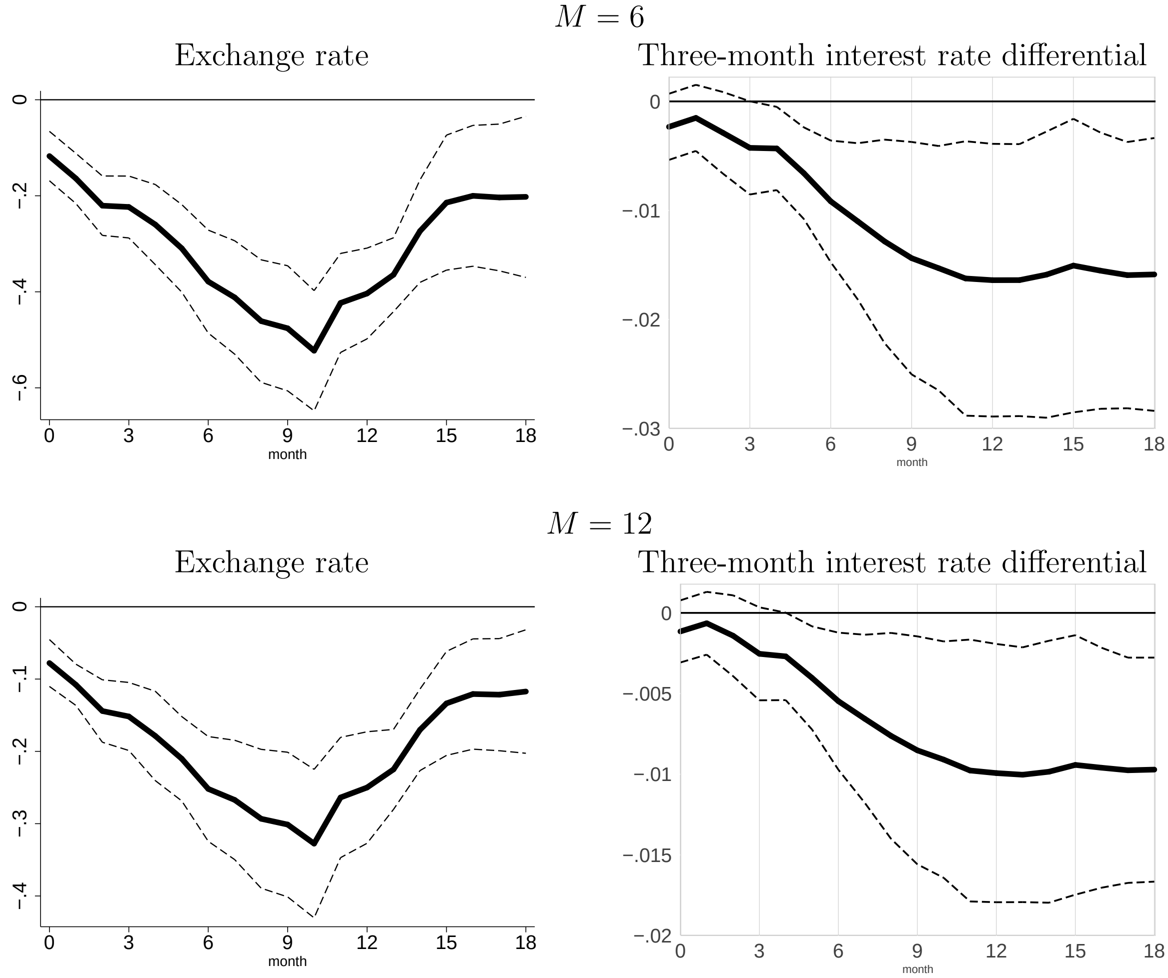
t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

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

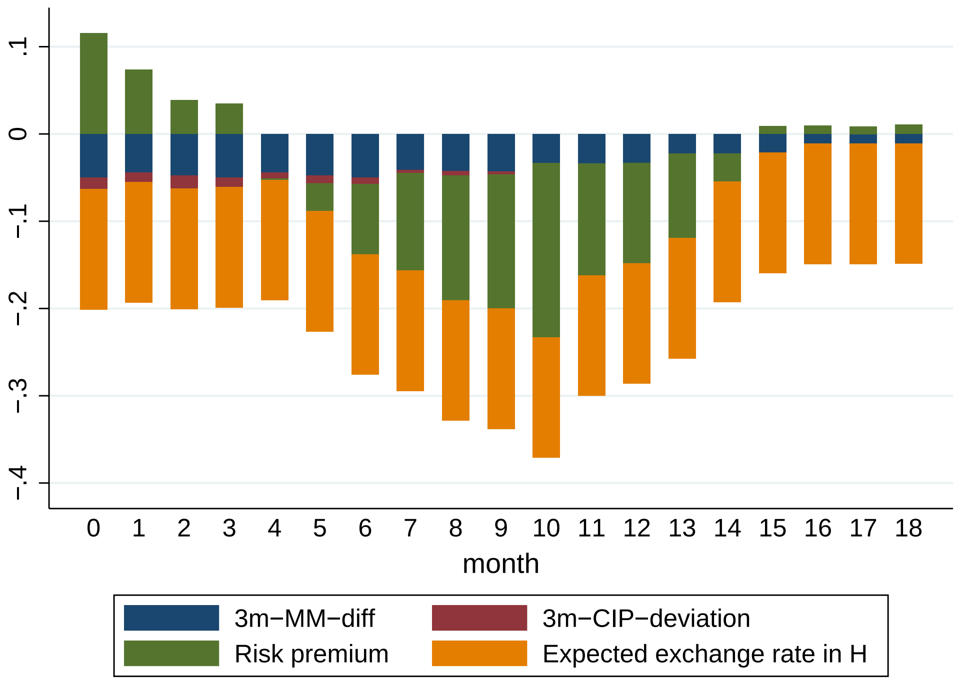
Appendix H. Web appendix — Additional figures

Figure H.7: Alternative choices of M



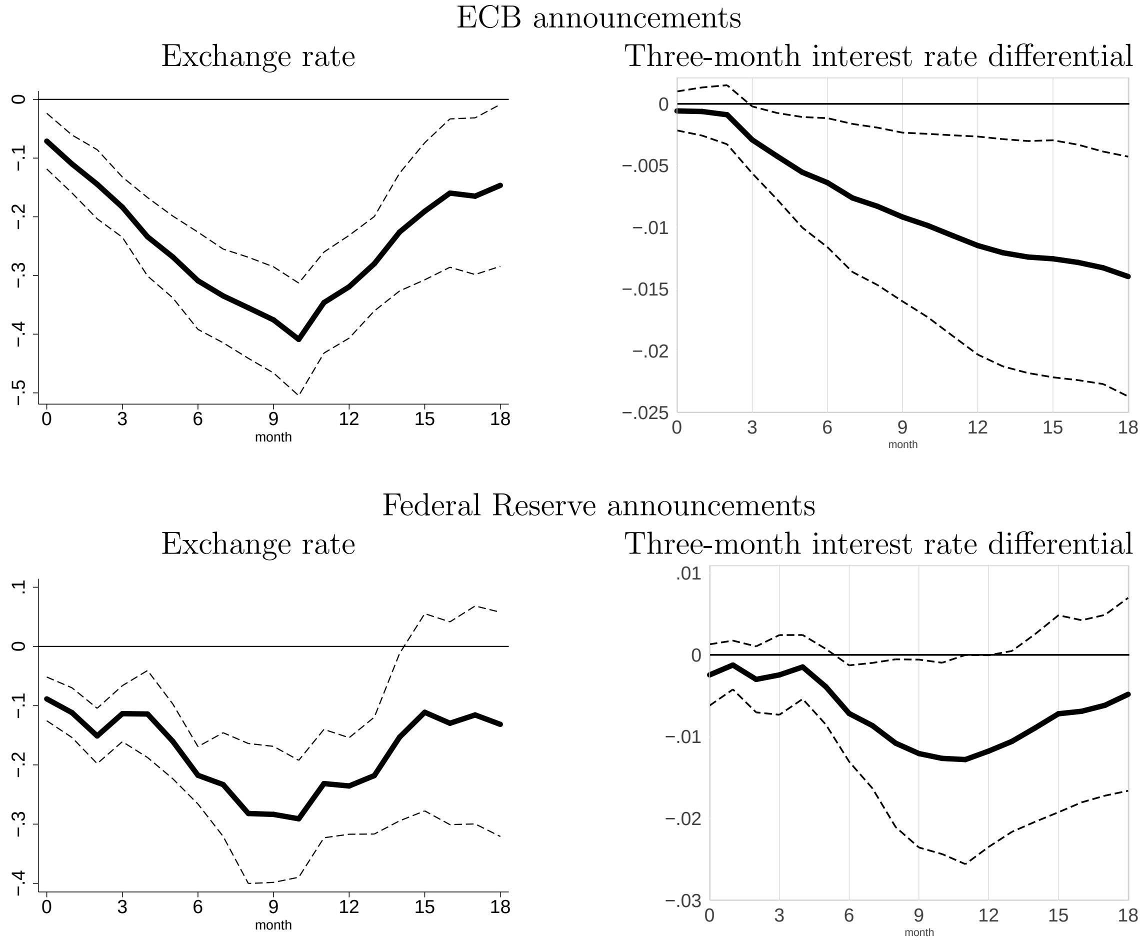
Note: The left-hand (right-hand) side panels present the estimates of the response of the US dollar-euro nominal bilateral exchange rate (three-month interest rate differential) to the relative QE shock that expands the ECB balance sheet relative to that of the Federal Reserve. The estimates are obtained from the two-stage least squares local projection regression in Equations (15) and (16) in the paper. The dashed lines represent 90% confidence bands based on the fixed-b heteroskedasticity-autocorrelation (HAC) robust standard errors introduced by Kiefer and Vogelsang (2005).

Figure H.8: Decomposition of exchange rate response to a relative ECB-Federal Reserve QE shocks



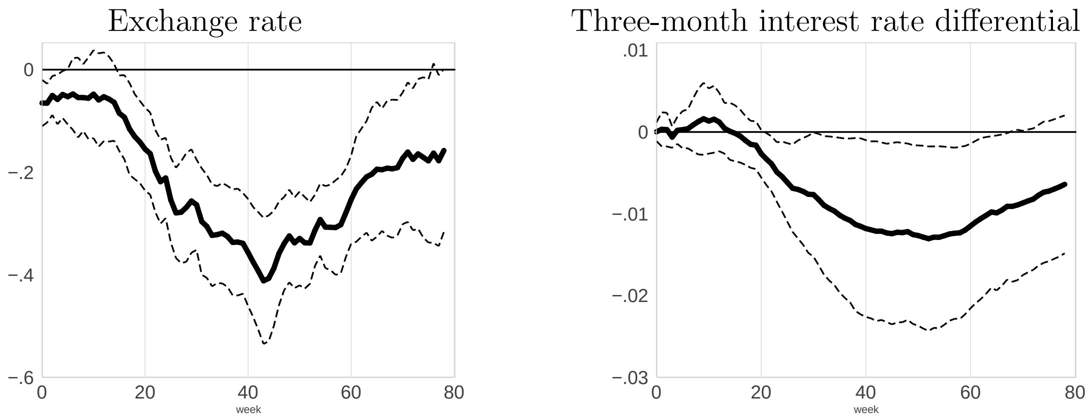
Notes: The panel shows the decomposition of the exchange rate effect of a relative QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point into the transmission channels according to Equation (F.12). The decomposition is calculated using only the estimates of the relevant impulse responses which are statistically significant at the 90% significance level, replacing the estimates which are not statistically significant by zero.

Figure H.9: Using only ECB or Federal Reserve QE announcements



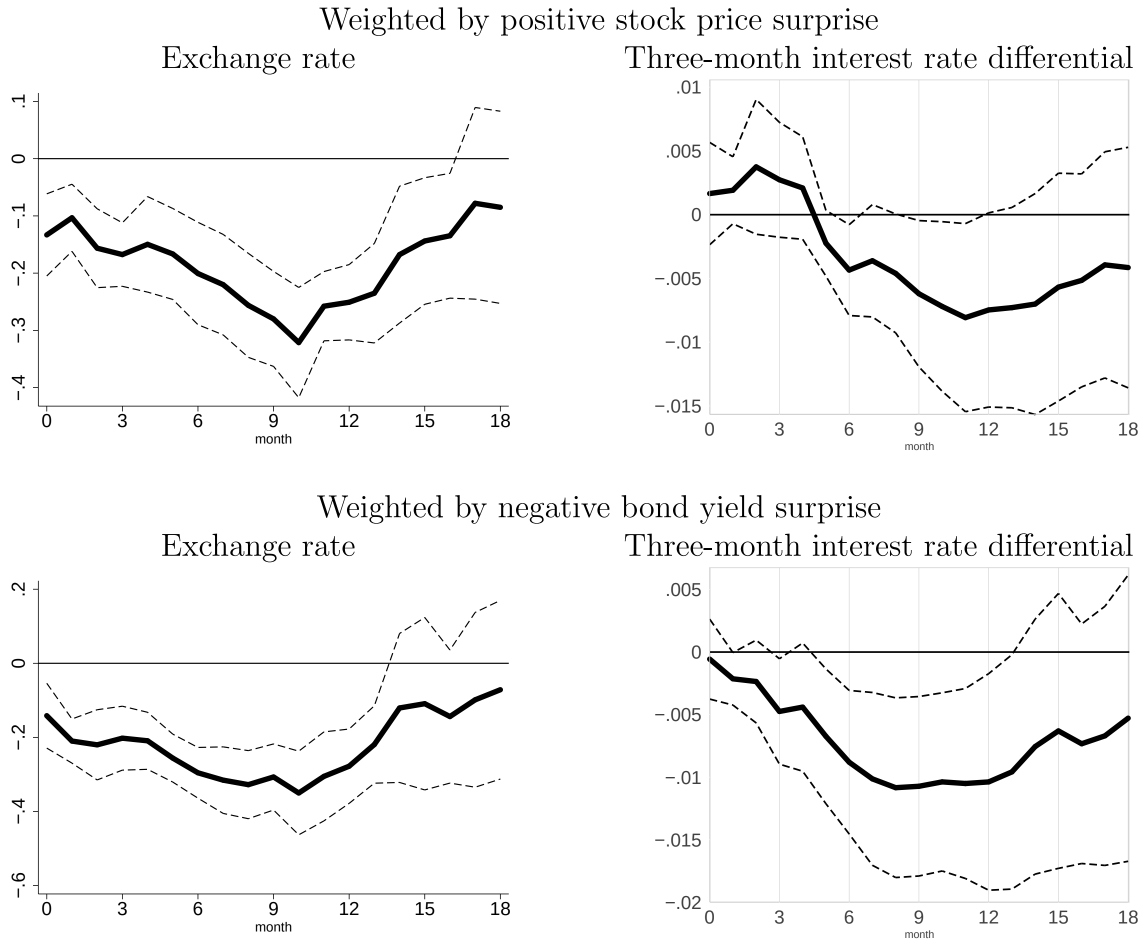
Note: See the note to Figure H.7.

Figure H.10: Weekly data, $BS_{t+36} - BS_{t-1}$



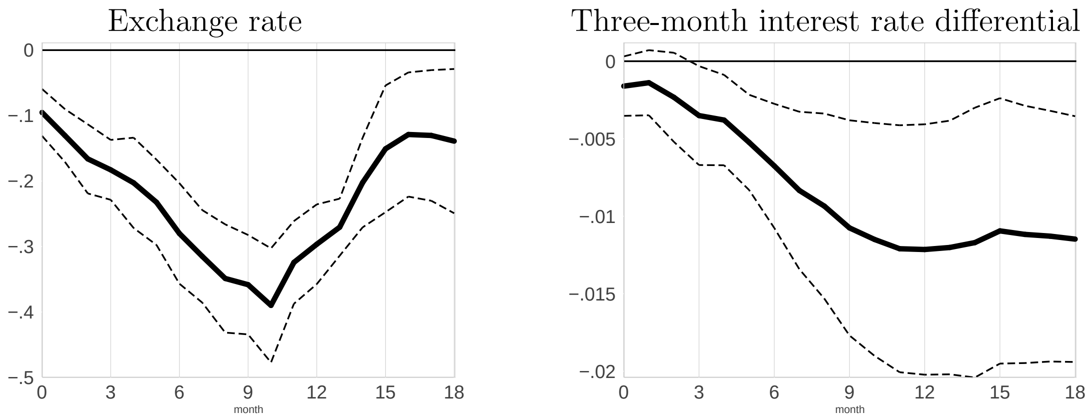
Note: See the note to Figure H.7.

Figure H.11: Weighting of announcement dummies



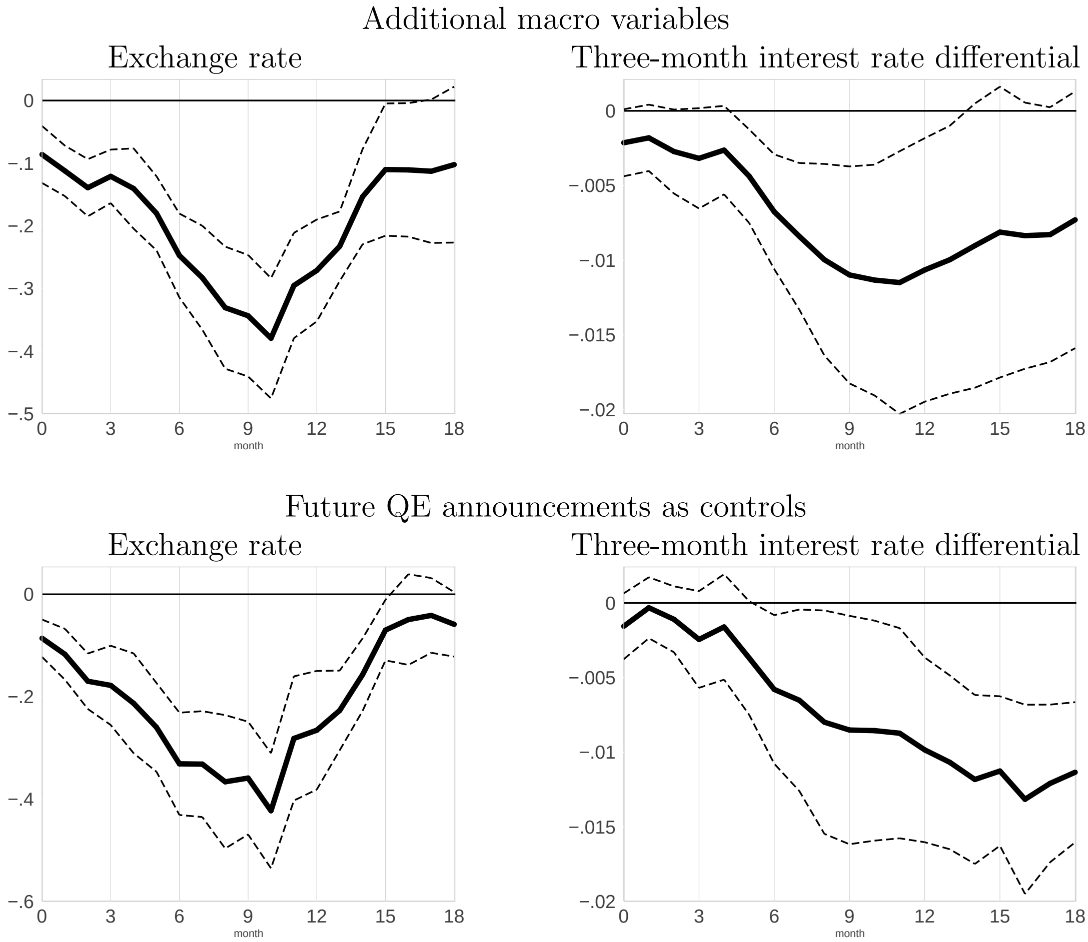
Note: See the note to Figure H.7.

Figure H.12: Rogers et al. (2014) announcements



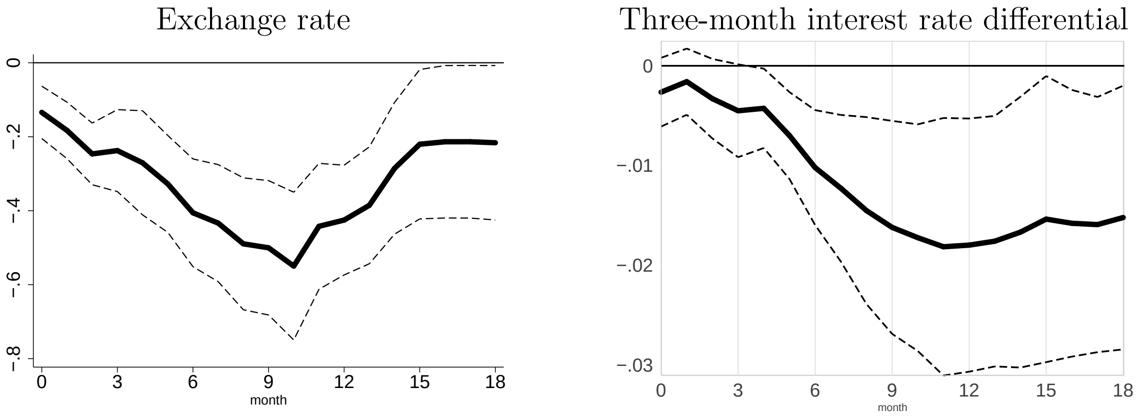
Note: See the note to Figure H.7.

Figure H.13: Additional macro variables and leads of QE announcements as controls



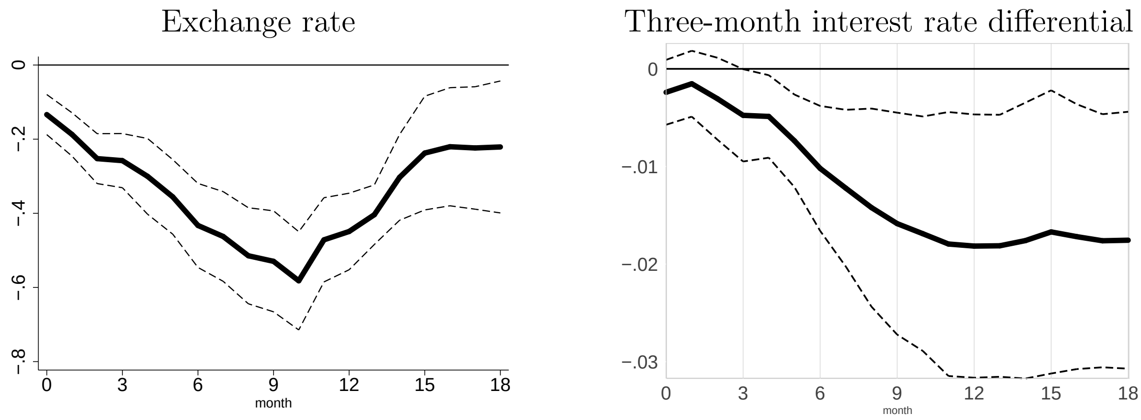
Note: See the note to Figure H.7.

Figure H.14: Generalising the law of motion of the relative central bank balance sheet, $BS_t = \delta_0 + \rho BS_{t-1} + \sum_{m=0}^{M} \eta_{t|t-m} + \boldsymbol{\delta}' \boldsymbol{e}_t$



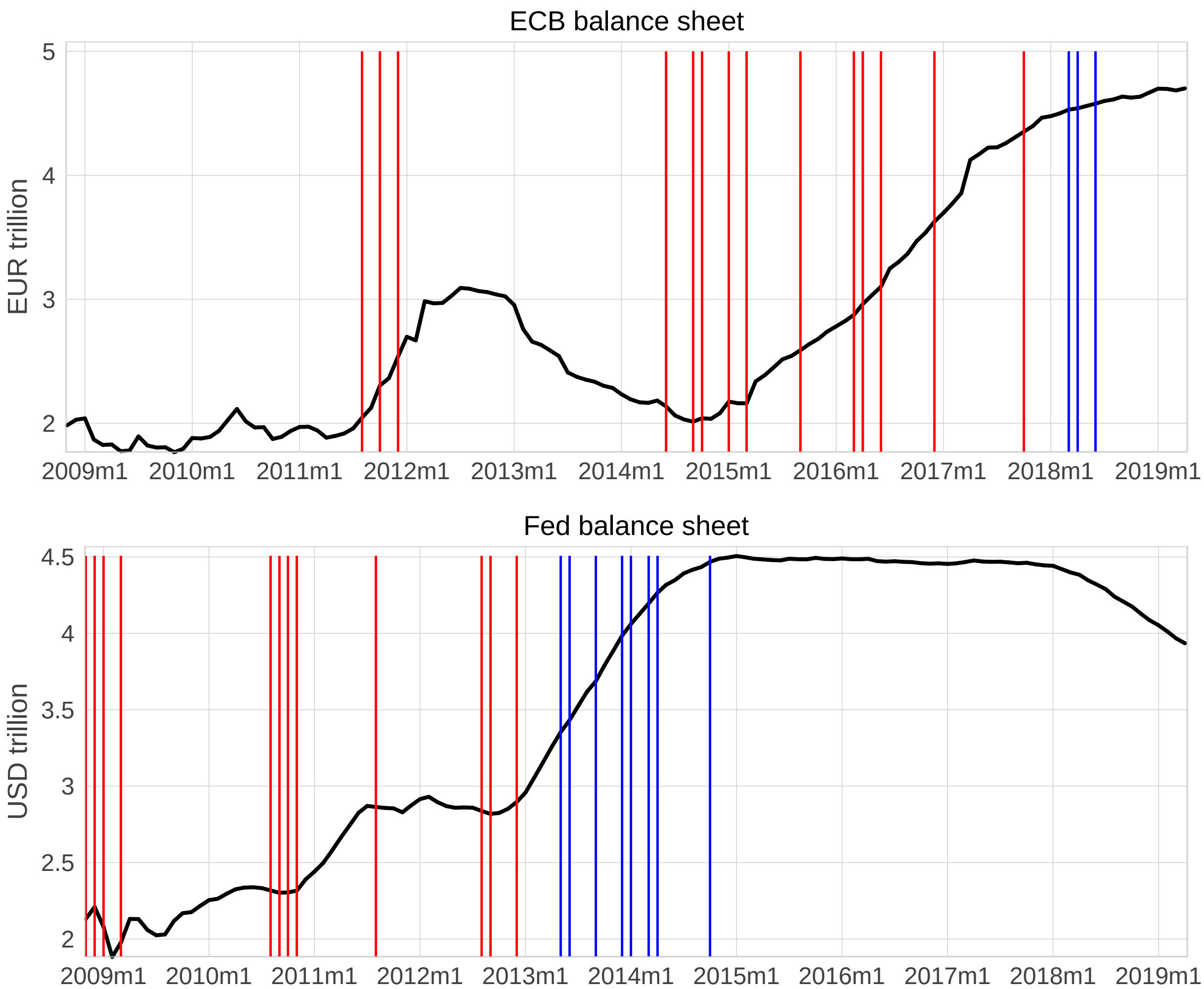
Note: See the note to Figure H.7.

Figure H.15: Generalising the definition of the QE shock, $\varepsilon_t^{qe} = \sum_{m=0}^{M} \phi^m \eta_{t+m|t}$



Note: See the note to Figure H.7.

Figure H.16: ECB and Federal Reserve balance sheets



Notes: The upper (lower) panel shows the balance sheet of the ECB (Federal Reserve). Red vertical lines indicate expansionary QE announcements, while blue vertical lines indicate tapering announcements.