Unconventional Monetary Policy and Covered Interest Rate Parity Deviations: is there a Link?

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Abstract

A fundamental puzzle in international finance is the persistence of covered interest rate parity (CIP) deviations. Since 2008, these deviations have implied a persistent dollar financing premium for banks in the Euro area, Japan and Switzerland. Using a model of the foreign exchange (FX) swap market, I explore two channels through which the unconventional monetary policies of the European Central Bank, Bank of Japan and Swiss National Bank can create an excess demand for dollar funding. In the first, quantitative easing leads to a relative decline in domestic funding costs, making it cheaper for international banks to source dollars via FX swaps, relative to direct dollar borrowing. In the second, negative interest rates cause a decline in domestic interest rate margins, as loan rates fall and deposit rates are bound at zero. This induces banks to rebalance their portfolio toward dollar assets, again creating a demand for dollars via FX swaps. To absorb the excess demand, financially constrained arbitrageurs increase the premium that banks must pay to swap domestic currency into dollars. I show empirically that CIP deviations have tended to widen around negative rate and QE announcements. I also document a rising share of dollar funding via the FX swap market for U.S. subsidiaries of Eurozone, Japanese and Swiss banks in response to a decline in domestic credit spreads.

Keywords: exchange rates, foreign exchange swaps, dollar funding, quantitative easing, negative interest rates

JEL Classifications: E43, F31, G15

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1 Introduction

Covered interest rate parity (CIP) is one of the most fundamental tenets of international finance. An arbitrage relationship, it states that the rate of return on equivalent domestic and foreign assets should be equal upon covering exchange rate risk with a forward contract. But deviations in excess of transaction costs have been a regularity for advanced economies since 2008 (Figure 1). CIP deviations are typically widest for the euro/\$, chf/\$ and yen/\$ pairs.[1] These deviations suggest Euro Area, Swiss and Japanese banks are paying a premium to swap euros, swiss francs and yen into dollars in the foreign exchange (FX) swap market. The initial deviation from CIP in 2008 was plausibly attributable to the financial crisis, during which increases in default risk for non U.S. banks in interbank markets translated into a significant premium for borrowing dollars. But the persistence of CIP deviations since then, and especially since 2014 is more difficult to explain, since measures of default risk in interbank markets have returned to pre-crisis levels.[2] One suspects that an explanation resting entirely on arbitrage frictions will be incomplete, given that the FX swap market is one of the deepest and most liquid financial markets, with an estimated 3 Trillion USD daily turnover (BIS, 2019). That markets in the specific currency pairs on which this paper focuses – the euro/\$, chf/\$ and yen/\$ -- are especially liquid reinforces the point.

I propose an explanation that focuses on unconventional monetary policies, specifically the quantitative easing (QE) and negative interest rates of the European Central Bank (ECB), Bank of Japan (BOJ) and Swiss National Bank (SNB). Since 2014, these central banks have adopted negative interest rates. They have undertaken asset purchases that increased the size of their balance sheets absolutely and relative to the Federal Reserve System (Figure 2).[3] To illustrate how these channels work, consider a Euro Area, Swiss or Japan bank desiring long-term USD funding. They can borrow those dollars directly at the USD funding cost, or alternatively can obtain them synthetically, by borrowing euros, swiss francs or yen and swapping them into dollars. The difference between the direct and synthetic dollar cost is equal to the CIP deviation. QE programs by the ECB, such as the Corporate Bond Purchase Program of 2016, entail purchases of privately-issued debt, with a consequent decline in domestic funding costs. All else equal, a European bank will borrow euros at a lower funding cost, and then swap into

[1] The euro/\$, chf/\$ and yen/\$ will be the three bilateral pairs that I focus on this paper. All pairs are measured with respect to the US dollar. This is the most relevant bilateral pair given the predominance of the US dollar as one of the two legs in a FX swap, and the euro/\$ and yen/\$ accounting for over 50% of all FX swap transactions.

[2] The typical way to measure default risk in interbank markets is the LIBOR-OIS spread, which is the difference between the London interbank offer rate (LIBOR) and the overnight index swap rate (ois).

[3] While the focus of the paper is on expansionary policies of the ECB, BOJ and SNB, the Federal Reserve has also pursued QE policies in the past. The last major expansion happened in 2012, with a tapering of QE beginning in late 2013.

dollars in the FX swap market. This leads to a reallocation of dollar funding toward FX swaps, which have become cheaper relative to direct dollar borrowing.

Negative interest rates, for their part, squeeze domestic interest margins because they reduce the returns on loans more than the cost of deposits, which cannot fall below zero. Lower domestic interest margins induce further portfolio rebalancing toward dollar assets, since relative returns on dollar assets are now higher. Assuming that banks seek to maintain a currency neutral balance sheet, a rising dollar asset position therefore leads to increased demand for dollar funding. Banks can satisfy this demand using FX swaps. Euro Area, Swiss and Japanese banks therefore swap euros, Swiss francs and yen for dollars, matching the currency composition of their assets and liabilities. Like QE, negative interest rates consequently result in an increase in bank demands for dollars via FX swaps.

Arbitrageurs are at the other end of these bank FX swap transactions. They provide the dollars that Euro Area, Swiss and Japanese banks seek in order to match their assets and liabilities. To satisfy a growing demand for dollar funding from banks, financially constrained arbitrageurs therefore raise the premium at which euros, yen and Swiss francs are swapped into dollars, causing a widening of CIP deviations.

To rationalize these two channels, I introduce a model with two agent types. The first agent is a non U.S bank that has a portfolio of domestic and dollar assets. They are funded by domestic deposits, dollar bonds and dollar funding obtained via FX swaps. The bank maximizes returns in a standard portfolio choice problem, yielding a demand for dollars in the FX swap market. The second agent is an arbitrageur, that takes the other end of the FX swap transaction. By borrowing in dollars at a risk-free rate, and lending them in the FX swap market, they make an arbitrage profit equal to the CIP deviation. Arbitrageurs are risk averse, and incur exchange rate risk that rises proportionally with the size of the swap position in the event that the counterparty defaults. An equilibrium in the FX swap market is defined by a market clearing condition; bank demands for dollar funding in the FX swap market are met by a supply of dollars by arbitrageurs.

I model QE as central bank purchases of privately-issued debt, in contrast to conventional QE that focuses on sovereign bond purchases. This allows central bank purchases to directly raise the price of privately issued debt and lower its yield.[4] In turn this compresses domestic credit spreads, defined as domestic bond yields in excess of the risk-free rate. This causes a wedge between the direct and synthetic dollar cost of funding, and causes the bank to reallocate dollar funding toward FX swaps. Arbitrageurs scale their balance sheet to supply dollars in the

[4]Implicitly, I am assuming private and public sector debt are imperfect substitutes. It is possible, however, for sovereign debt purchases to have a similar effect in causing a decline in bank funding costs. This would be the case if banks are actively issuing sovereign bonds in the secondary market as a source of funding. However, as a notational convenience in the model, I only consider private sector purchases as being able to directly affect the domestic credit spread.

FX swap market. To absorb the increased demands, they demand a higher forward premium and profit from the arbitrage trade. Therefore, CIP deviations widen in equilibrium.

To analyze the effects of negative rates, I assume differential pass-through of the central bank rate to loan and deposit rates. As the central bank rates become negative, loan rates fall, but that deposits rates fall by less because they are bounded below by zero. This squeezes domestic interest rate margins, and the risk-adjusted return on dollar assets therefore increases relative to the risk-adjusted return on domestic assets. Banks consequently shift the composition of their portfolios toward additional dollar assets. This results in an increased demand for dollars obtained via FX swaps. Arbitrageurs absorb the increased demands for dollar funding by increasing the forward premium of the arbitrage trade. This causes CIP deviations to widen. The effects on prices are thus directionally the same as in the case of QE.

I then take testable implications of the model to the data. First, I first document high-frequency evidence on CIP deviations for the euro/$, yen/$ and chf/$ around the time of scheduled negative interest rate and QE announcements. I then generalize this result using surprises to interest rate futures around scheduled monetary announcements by the ECB, BOJ and SNB. The identifying assumption is that changes in interest rate futures on announcement days respond only to monetary news. I conduct a panel regression framework in which I test the aggregate effect of monetary surprises across the term structure of CIP deviations for the euro/$, chf/$ and yen/$ pairs. In particular, I test for a regression discontinuity in the sensitivity of CIP deviations to monetary surprises, with the model predicting a higher sensitivity during the period of unconventional monetary policy. Consistent with the model prediction, I find a 1 basis point expansionary monetary surprise by the ECB, SNB and BOJ leads to a widening of CIP deviations by approximately 0.3 to 0.8 basis points for all 3 pairs during the period of unconventional monetary policy. This result is robust to using alternative benchmarks, with similar results for a CIP deviation based on LIBOR or Treasury rates.

The second set of empirical evidence deals with quantity effects. A testable prediction of the model is that both QE and negative interest rates should lead banks in the Eurozone, Japan and Switzerland to reallocate dollar funding toward FX swaps. I proxy for holdings of FX swaps through data from Chicago Federal Reserve Call Reports. The dataset constains information on the balance sheet of U.S. subsidiaries of Eurozone, Japanese and Swiss banks. The specific balance sheet item I use is interoffice flows, which are defined as net borrowings of the U.S. subsidiary from the parent. For the purposes of my analysis, I assume interoffice flows represent borrowings in euros, swiss francs and yen that are swapped into dollars. This is plausible given U.S. based subsidiaries are likely operating a dollar balance sheet, and the parent operates a balance sheet primarily in domestic currency. Based on this data, I find that a decline in domestic credit spreads causes a rise in the share of total assets funded by interoffice flows. This is consistent with the model, which predicts a reallocation of dollar funding toward

FX swaps in response to QE.

Related Literature. Since 2008, there have been a number of proposed factors to explain CIP deviations. They can be divided broadly into two strands, factors that stress CIP deviations are predominantly driven by constraints on the supply of dollars available for FX swaps, and factors that stress the demand for dollar funding by cross-border banks. On the supply front, explanations range from rising counterparty risk during the financial crisis Baba and Packer (2009), rising balance sheet costs and regulatory requirements (Du et al., 2018a; Liao, 2020; Bräuning and Puria, 2017; Cenedese et al., 2019), the strengthening of the dollar in limiting risk bearing capacity (Avdjiev et al., 2016), and rising bid-ask spreads due to limited arbitrageur capacity (Pinnington and Shamloo, 2016). Within the literature on supply factors, the most compelling evidence is provided in Du et al. (2018b), which find significant rises in short-term (<3 month) CIP deviations at quarter-ends as banks off-load their holdings of short-term swap contracts Du et al. (2018a). Similarly, Cenedese et al. (2019) use micro-level evidence and show that dealers that are more leveraged are more sensitive to structural imbalances in the FX swap market, and price significantly higher forward premia, and CIP deviations.

A second strand deals with demand side factors for dollar funding in the FX swap market. This includes the impact of monetary policies, (Bahaj and Reis, 2018; Iida et al., 2016; Borio et al., 2016; Dedola et al., 2017; Du et al., 2018a; Bräuning and Ivashina, 2017), shocks to dollar funding for European banks during the sovereign debt crisis (Ivashina et al., 2015), and differences in funding costs across currencies (Syrstad, 2018; Rime et al., 2017; Liao, 2020; Kohler and Müller, 2018). I make two empirical contributions to this literature. First, I use market-based measures of underlying interest rate futures around monetary announcements and document a systematic effect of monetary surprises on CIP deviations. Second, I provide evidence on quantities, using data on interoffice flows of U.S. subsidiaries of banks in the Euro area, Japan and Switzerland. Taking these as a proxy for holdings of FX swaps, I find an increase in the share of dollar funding sourced via FX swaps in response to a decline in domestic funding costs.

I also contribute to a recent literature on modeling CIP deviations. These models focus on factors increasing limits to arbitrage, either by imposing an outside cost of capital, or by tightening balance sheet constraints of arbitrageurs supplying dollars in the FX swap market (Vayanos and Vila, 2009; Ivashina et al., 2015; Liao, 2020; Gabaix and Maggiori, 2015; Avdjiev et al., 2016; Sushko et al., 2017; Greenwood et al., 2019; Gourinchas et al., 2019). I contribute to this literature by formalizing the channels through which monetary policy can cause a rise in bank demands for dollar funding in the FX swap market. In particular, I examine the role of both negative interest rates and QE and show how these policies affect the trade-off between direct and synthetic dollar funding via FX swaps. In the optimal allocation, direct and synthetic dollar funding costs are equated. This gives rise to a condition in which the CIP deviation reflects differences in dollar and domestic credit spreads.

My paper also draws on an empirical literature on the effects of unconventional monetary policy on both funding costs and bank profitability. Studies have shown that both corporate and sovereign bond purchase programs have an effect in reducing domestic bond yields (Abidi et al., 2017; Koijen et al., 2017), and the impact of negative interest rates on bank profitability (Ampudia and Van den Heuvel, 2018; Altavilla et al., 2018; Borio and Gambacorta, 2017; Lopez et al., 2018; Claessens et al., 2018). For example,Abidi et al. (2017) find that the corporate asset purchase program (CSPP) implemented by the ECB in 2016 led to a decline in yields of approximately 15 basis points for bonds that satisfied the conditions for purchase.[5] This evidence motivates my assumption that the effects of QE are via reducing domestic credit spreads, which in turn causes the bank to substitute toward dollar funding sourced via FX swaps. The literature on negative rates find evidence on a decline in net interest income. This supports the channel of negative interest rates in my paper, as my theory is that a decline in a bank's domestic net interest income then causes a rebalancing of the portfolio to hold more dollar assets. To hedge the balance sheet, this in turn causes a rise in dollar funding via FX swaps.

Finally, my paper speaks to the rising role of the dollar in cross-border banking and mutual fund holdings (Bergant et al., 2018; Maggiori et al., 2020; Goldstein et al., 2018). In Bergant et al. (2018),they find asset purchase programs by the ECB in 2016 led banks in the Eurozone to significantly increase their exposure to US dollar denominated assets. Similarly, Maggiori et al. (2018) document a secular trend since 2008 of rising dollar and falling euro share based on data on mutual fund portfolios. The findings of these papers support a general trend of portfolio rebalancing toward dollar assets in both the corporate and financial sector. This supports the portfolio rebalancing channel, in which negative rates causes a rebalancing toward dollar assets, which then creates a hedging demand for dollars in the FX swap market.

Roadmap. The rest of the paper is structured as follows. In section 2, I present some stylized facts on the FX swap market. In section 3, I introduce the model, with a setup of the agents, solution for optimal demand and supply of FX swaps, and an analysis of the effects of QE and negative rates on the CIP deviation. In section 4, I provide empirical evidence on the effect of monetary policy announcements on credit spreads and the CIP deviation, as well as cross-sectional evidence on bank holdings of FX swaps. Section 5 concludes.

[5] They use a regression discontinuity design, in which they compare bonds that are accepted by CSPP to bonds that are similarly rated but just below the threshold to be eligible for CSPP. The identifying assumption is that the classification of bonds by credit standards are exogenous to macroeconomic conditions and other shocks that affect yields.

2 Motivating Facts

The following facts provide empirical evidence that I explore through the lens of the model. The first fact states that there is an observed positive correlation between the level of the interest rate differential and the CIP deviation. Second, I show that once you construct a measure of CIP deviations that takes into account differences in funding costs across currencies, this measure is much closer to parity for the euro/$ and yen/$ pairs. Before I outline the facts, I will briefly cover two important definitions, how CIP deviations are measured, and FX swaps.

Covered interest rate parity (CIP) states that two assets with identical characteristics in terms of credit risk and maturity, but denominated in different currencies, have the same rate of return after accounting for exchange rate risk using a forward contract. To illustrate, let us consider an investor that can borrow at the risk-free rate in dollars or euros. The total cost of borrowing 1 dollar directly is $1 + r^f_\$$. Alternatively, the investor can borrow dollars via the FX swap market. To do so, they borrow $\frac{1}{S}$ euros, where S is the quotation in dollars per euro. The total cost in euros is then $\frac{1+r^f_d}{S}$. They then hedge exchange rate risk with a forward contract, which gives a synthetic dollar cost of $\frac{F}{S}(1 + r^f_d)$. The CIP deviation is defined as the difference between the direct and synthetic dollar borrowing cost, which we formally state in equation 1.

$$\Delta = \underbrace{1 + r^f_\$}_{\text{direct}} - \underbrace{\frac{F}{S}(1 + r^f_d)}_{\text{synthetic}} \tag{1}$$

Since 2008, European, Swiss and Japanese Banks have been paying a a higher synthetic dollar cost to borrow dollars in the FX swap market, and the CIP deviation can therefore be interpreted as a synthetic dollar borrowing premium.

Foreign exchange swaps

Foreign exchange swaps, also known as spot-forward contracts, are used by banks and corporates to hedge balance sheet risk. To give perspective on how widespread it is used in financial markets, foreign exchange swaps are the most traded foreign exchange instrument worldwide, with a turnover of approximately \$3.2 Trillion USD. This accounts for nearly half of global turnover of \$6.6 Trillion USD based on the BIS triennial survey, with spot foreign exchange accounting for only \$2.0 Trilion USD.

A bank may hedge the FX exposure due to a mismatch of their currency assets or liabilities, with evidence in Borio et al. (2016) that Japanese banks have significantly higher dollar assets than liabilities, causing them to turn to the FX swap market for dollar funding. [6] We illustrate

[6] Similarly, a corporate may hedge the currency mismatch of their cash flows, for example if a European corporate has profits in dollars from their offshore activities, they will hedge the Foreign exchange risk by swapping their

the legs of the FX swap in Figure 3. The swap is a euros for dollars swap. In the first leg of the contract, the customer exchanges a principal of X Euros at the current spot rate S dollars per Euro. The customer receives SX Dollars. Both parties then agree to re-exchange the principals at maturity at a specified forward rate, this is known as the forward leg of the contract. The customer receives their X Euros, and the dealer then receives FX Dollars, where F is the forward rate of the contract.

At maturities of greater than 3 months, the predominant risk hedging instrument is a cross-currency swap. A cross-currency swap begins with an exchange of principals at a spot rate, which we illustrate in Figure 4. For illustration, let us suppose the customer engages in a 10 year swap, with the customer receiving SX Dollars and the dealer receiving X Euros as before. For every 3 months until maturity, the customer pays 3 month USD Libor interest payments, and the dealer in return pays 3 month Euro Libor plus the addition of the cross-currency basis. At maturity of the contract, the principals are then re-exchanged at the initial spot rate. The dealer of a cross-currency swap sets the cross-currency basis Δ.

In this paper, we deal primarily with cross-currency swaps. This is the primary use of hedging for banks with long-term funding, and is more applicable in our setting, which considers a U.S. subsidiary of a Euro area, Japan or Swiss Bank considering long term funding. In particular, QE programs, through the lens of the model, impacts long term funding costs. Therefore the impact of monetary policies are more pronounced on CIP deviations at longer maturities, whereas other factors, such as regulatory constraints, may play a role for short-term FX swaps.[7]

Stylized Fact #1 *In the cross-section, high interest rate currencies have a more positive CIP deviation.*

Examining a set of advanced economies, countries with a higher interest rate typically have a more positive CIP deviation (Figure 5).[8] Consider an example of a bank pursuing a carry trade strategy, in which banks borrow in a low interest rate currency, the yen, and go long in the dollar. This strategy yields a positive return given the tendency for high interest rate currencies to appreciate on average. But if banks pursue an extensive carry trade strategy, the build up of dollar assets require dollar funding via FX swaps to hedge FX risk. In the event hedging demands by banks for dollars in the FX swap market cannot be fully absorbed by arbitrageurs, this results in an increase in the premium at which yen is swapped into dollars.

The non-zero slope in Figure 5 is also an indication that limits to arbitrage matter. For example, to conduct CIP arbitrage, an agent would borrow in dollars at a risk-free interbank

dollar receivables with euros.

[7]See Du et al. (2018a) for effects of quarter-end reporting regulations on CIP deviations of short-term maturities.

[8]The relationship in Figure 5 is positive for the period since 2008, however it is a stronger correlation for the period since 2014.

rate, swap dollars into yen and invest in the equivalent yen denominated asset. This will earn a premium equal to the absolute value of the yen/$ CIP deviation. Without limits to arbitrage, arbitrageurs will fully absorb the hedging demands of banks, and the slope should be zero.[9]

Stylized Fact #2 *CIP deviations are much smaller when accounting for differences in funding costs across currencies*

The channel of QE works through easing domestic funding costs. In other words, following a QE asset purchase program, a domestic bank can now obtain liquidity in euros, Swiss francs and yen with relative ease compared to direct dollar funding. Therefore, CIP deviations based on an interbank rate like LIBOR and the overnight index swap (OIS) rate do not take into account the true funding costs in the respective currencies of the swap. Given bank funding costs are typically higher in USD, a measure of CIP deviations that takes into account funding costs should be much closer to parity. In Figure 6, I compare a measure of the 5 year CIP deviation for the euro/$ and yen/$ pairs, against a measure that includes the differences in funding costs. To account for funding costs, I use data on bank credit spreads obtained from Norges Bank for a set of A1 rated French and Japanese banks. Credit spreads measure the excess of the bond yield above a risk-free rate, and provide a measure of the relative cost of funding across currencies.Once the CIP deviation is adjusted for differences in funding costs, these deviations are smaller in magnitude and closer to parity.[10] This finding is consistent with other papers that document CIP deviations in risk-free rates are much smaller when taking into account the funding liquidity premium of the USD (Syrstad, 2018; Rime et al., 2017; Liao, 2020; Kohler and Müller, 2018).

3 Model

I introduce a model with two agents, a domestic (non U.S.) bank and arbitrageurs. To simplify the setting, I consider a bank with headquarters domiciled outside the U.S, and a subsidiary located in the U.S. The bank therefore invests in domestic assets at home, or in dollar assets through the subsidiary. The bank has two ways of borrowing dollars. They can borrow directly via wholesale funding or issuing dollar denominated debt, or alternatively, by borrowing in domestic currency from the headquarters and then swapping into dollars in the FX swap market. In equilibrium the bank chooses a level of domestic and dollar assets that maximizes a risk-adjusted return. The bank also chooses an allocation of direct and synthetic dollar funding such that marginal costs of each funding source are equalized.

Arbitrageurs are the intermediaries through which banks settle transactions in the FX swap

[9]Indeed, the slope of Figure 5 is zero for the pre-2008 period.

[10]Mathematically, I account for credit spreads by constructing the following measure: $\Delta + \ell_{\$} - \ell_d$, where Δ is the cross-currency basis, $\ell_{\$}$ is the dollar credit spread, and ℓ_d is the domestic credit spread.

market. As they take the other end of the swap, they supply dollars in exchange for the domestic currency. Arbitrageurs are risk averse, and in the event of default, incur exchange rate risk that rises with the size of the swap position. This imposes a limit to arbitrage, and means they satisfy a growing demand for dollar funding from banks by resetting the forward rate, and therefore increase the premium banks pay to swap domestic currency into dollars. In equilibrium, market clearing requres a forward rate such that arbitrageurs fully absorb the demands for dollar funding by banks.

Arbitrageur

Following Sushko et al. (2017), I model a arbitrageur that has expected exponential utility over next period wealth W_{t+1}. Formally, I define $U_t = E_t\left[-e^{-\rho W_{t+}}\right]$, where ρ is a measure of risk aversion. arbitrageur wealth in period $t+1$ is equal to the dollar asset return on prior period wealth, and a return on lending dollars in the swap market. The arbitrageur exchanges principals at a specified spot exchange rate s_t dollars per unit of domestic currency, with an agreement to re-exchange principals at maturity at forward rate f_t. The arbitrageur bears exchange rate risk. In the event of a default with a given probability θ, the arbitrageur does not earn the forward premium $f_t - s_t$ on the trade, but instead earns a stochastic return based on the realized spot rate exchange rate s_{t+1}.

$$W_{t+1} = W_t(1+r^f_\$) + (1-\theta)x_{\$,t}(f_t - s_t + r^f_d - r^f_\$) + \theta x_{\$,t}(s_{t+1} - s_t + r^f_d - r^f_\$) \tag{2}$$

The CIP deviation, Δ_t, is defined as the excess of the forward premium over the interest rate differential, $\Delta_t = f_t - s_t - (r^f_\$ - r^f_d)$. I can rewrite equation 2 as the sum of returns on initial wealth, CIP arbitrage profits and the difference between the actual spot rate at t+1 and the forward rate.

$$W_{t+1} = \underbrace{W_t(1+r^f_\$)}_{\text{return on wealth}} + \underbrace{x_{\$,t}\Delta_t}_{\text{cip arbitrage}} + \underbrace{\theta x_{\$,t}(s_{t+1} - f_t)}_{\text{counterparty risk}}$$

I assume $s_{t+1} \sim N(f_t, \sigma^2_s)$. Drawing on the properties of the exponential distribution, maximizing the log of expected utility is equivalent to mean-variance preferences over wealth[11].

$$\max_{x_{\$,t}} \rho\left(W_t(1+r^f_\$) + x_{\$,t}\Delta_t - \frac{1}{2}\rho\theta^2 x^2_{\$,t}\sigma^2\right) \tag{3}$$

[11] To derive this formula, note that $U_t = -e^{-\rho\left(W_t(1+r^f_\$)+x_{\$,t}\Delta_t - \theta x_{\$,t}f_t\right)}E_t e^{-\rho\theta x_{\$,t}s_{t+1}}$. Using the properties of the exponential distribution, $E_t e^{-\rho\theta x_{\$,t}s_{t+1}} = e^{-\rho\theta x_{\$,t} - \frac{1}{2}\rho\theta^2 x^2_{\$,t}\sigma^2}$. Taking logs and simplifying yields the expression in equation 3.

The optimal supply of dollars by a arbitrageur is given by $x^*_{\$t}$.

$$x^*_{\$t} = \frac{\Delta_t}{\rho\theta^2\sigma^2} \tag{4}$$

Taking the CIP deviation as given, a rise in counterparty risk, exchange rate risk and risk aversion lead to a lower supply of dollars.[12]

Bank

I consider an International bank with headquarters domiciled outside the U.S. At headquarters, the bank operates the domestic currency side of the balance sheet, and invests in domestic assets, A_d, and holds domestic deposits D. Meanwhile, the bank's U.S. subsidiary is in charge of the dollar currency side of the balance sheet. The subsidiary has access to direct dollar funding $B_\$$, and invests in dollar assets $A_\$$ on behalf of headquarters. Headquarters also provide domestic currency funding to its U.S. subsidiary, which are then swapped into dollars. I denote this as the level of synthetic dollar funding $x^D_\$$. A stylized representation of the consolidated balance sheet is illustrated in Figure 7. The balance sheet reports the assets and liabilities of headquarters and its U.S. subsidiary.

The asset returns are stochastic with distributions $\tilde{y}_d \sim N(y_d, \sigma^2_d)$ and $\tilde{y}_\$ \sim N(y_\$, \sigma^2_\$)$, and with covariance $\sigma_{d,s}$. The borrowing cost on domestic deposits c_d is assumed fixed. The cost of direct dollar borrowing is the sum of the dollar credit spread $l_\$$ and the risk-free rate in dollar borrowing, $r^f_\$$. To obtain dollars synthetically, the bank first issues a domestic currency bond with a yield equal to the addition of the credit spread l_d and a risk-free rate r^f_d. It then engages in a FX swap, paying the forward premium $f - s$ to swap domestic currency into dollars. In addition to these costs, I also impose an imperfect substitutability between direct and synthetic dollar funding, by imposing a convex hedging cost in swapping domestic currency into dollars via FX swaps.

Definition [Convex Hedging Cost]: *Hedging cost in FX swap $F(x^D_\$)$ is convex, with $F'(.) > 0$ and $F''(.) > 0$.*

Empirical evidence in support of convex hedging costs is found in Abbassi and Bräuning (2018). Using detailed FX swap trades for a set of German banks, they find that banks that have to pay a dollar borrowing premium that is increasing in the size of their dollar funding gap, which is the amount of dollars obtained via FX swaps to hedge currency exposure. They interpret this result as reflecting a higher shadow cost of capital for a bank with a larger

[12]As the subject of this paper is to focus on demand side factors, the parameters governing supply are assumed constant. However, in times of severe stress in interbank markets, rises in counterparty risk and risk aversion are critical to understand the widening of the euro/\$, yen/\$ and chf/\$ CIP deviation during the financial crisis of 2008, and subsequently in the euro crisis.

funding gap. This is because regulators impose capital charges on bank balance sheets that have unhedged currency exposure. Other reasons for a convex hedging cost include the cost of providing dollar collateral. As the size of the swap position increases, the bank is required to post an increasing amount of dollar collateral for the arbitrageur to accept the transaction. Regulations on interoffice funding of US branches of foreign (non U.S.) banks may also be a factor. For example, a tax on interoffice flows, such as the BEAT tax implemented in 2018, makes synthetic dollar funding more costly, all else equal.[13] The convex hedging cost has the additional property of creating an imperfect substitution between the direct and synthetic sources of dollar funding. This is consistent with banks in practice, as U.S. subsidiaries typically have a mix of direct and synthetic dollar funding.[14]

Portfolio Problem

The bank maximizes the value of the portfolio after the realization of asset returns, subject to equations 6,7,8 and 9. Equation 6 is a value at risk constraint which determines the optimal risk-adjusted weights of domestic and dollar assets. This constraint is also seen in Adjiev et al (2016).[15] Equation 7 states that bank equity K is the difference between total assets and total liabilities. Equation 8 states that the balance sheet of the bank is currency neutral, and dollar assets are entirely funded by direct or synthetic dollar funding. This is consistent with banking regulations that are designed to impose capital charges on banks that have unhedged currency exposure Abbassi and Bräuning (2018). Equation 9 is a constraint on dollar denominated debt to be within a fraction γ of bank capital. To justify this constraint, in practice, non U.S. banks direct dollar borrowing is relatively uninsured compared to domestic currency liabilities for a non U.S. bank.[16]

[13] For more details on the BEAT tax, please refer to a recent Financial Times article, https://ftalphaville.ft.com/2018/03/23/1521832181000/Cross-currency-basis-feels-the-BEAT/. The article clearly states that as U.S. subsidiaries now have to pay a tax on interoffice funding they obtain from headquarters. This also has the indirect effect of causing a substitution toward commercial paper markets as a direct consequence of interoffice flows being taxed.

[14] For details of U.S. subsidiaries of foreign (non U.S.) banks share of synthetic dollar funding, please refer to Table 6 for more details. I find that for the majority of U.S. subsidiaries, there is typically a mix of synthetic and direct dollar funding.

[15] In Avdjiev et al. (2016) the authors consider a setup of a bank that is engaged in supplying dollars in the FX swap market, and has a portfolio of dollar and foreign (euro) assets. My paper takes a different approach, as I am separating the bank and arbitrageur arms. In my model, the bank is demanding dollars via FX swaps, and the arbitrageur is supplying dollars.

[16] For example, consider the U.S. subsidiary of a non U.S. bank. They typically have lower credit ratings, and do not have the equivalent level of deposit insurance as a U.S. domiciled bank.

$$\max_{A_{d,t},A_{\$,t},x^D_{\$,t},B_{\$,t},D_{d,t}} V_{t+1} = \tilde{y}_d A_{d,t} + \tilde{y}_\$ A_{\$,t} - (\ell_\$ + r^f_\$)B_{\$,t} - (\ell_{d,t} + r^f_d + f_t - s_t)x^D_{\$,t,} - c_d D_{d,t} - F(x^D_{\$,t}) \tag{5}$$

Subject to

$$a^T \Sigma a \leq \left(\frac{K}{\alpha}\right)^2, a = \begin{bmatrix} A_{d,t} & A_{\$,t} \end{bmatrix}^T \Sigma = \begin{bmatrix} \sigma_d^2 & \sigma_{d,\$} \\ \sigma_{d,\$} & \sigma_\$^2 \end{bmatrix} \leq \left(\frac{K}{\alpha}\right)^2 \tag{6}$$

$$K = A_{d,t} + A_{\$,t} - D_{d,t} - B_{\$,t} - x^D_{\$,t} \tag{7}$$

$$A_{\$,t} = x^D_{\$,t} + B_{\$,t} \tag{8}$$

$$B_{\$,t} \leq \gamma K \tag{9}$$

The first order conditions with respect to $A_{d,t}$, $A_{\$,t}$, $x^D_{\$,t}$, $D_{d,t}$ and $B_{\$,t}$ are shown in equations 10 to 13, where the Lagrangian for constraints 6,7,8 and 9 are given by ϕ_t, μ_t λ_t and ξ_t.

$$\begin{matrix} A_{d,t}: \\ A_{\$,t}: \end{matrix} \quad \begin{bmatrix} y_d \\ y_\$ \end{bmatrix} - 2\phi_t \Sigma \begin{bmatrix} A_{d,t} \\ A_{\$,t} \end{bmatrix} - \begin{bmatrix} \mu_t \\ \mu_t + \lambda_t \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{10}$$

$$x^D_{\$,t}: \quad -(\ell_{d,t} + r^f_d + f_t - s_t) - F'(x^D_{\$,t}) + \lambda_t + \mu_t = 0 \tag{11}$$

$$D_{d,t}: \quad -c_d + \mu_t = 0 \tag{12}$$

$$B_{\$,t}: \quad -\ell_\$ - r^f_\$ + \mu_t + \lambda_t - \xi_t = 0 \tag{13}$$

Using equations 11 and 13, I can express the relation between direct and synthetic dollar borrowing costs in equation 14.

$$\underbrace{\ell_{d,t} + r^f_d + f_t - s_t + F'(x^D_{\$,t})}_{\text{synthetic dollar cost}} = \underbrace{\ell_{\$,t} + r^f_\$ + \xi_t}_{\text{direct dollar cost}} \tag{14}$$

This condition can be interpreted as a law of one price in bond issuance, after covering exchange rate risk with a forward contract. Recall that the CIP deviation is defined as the excess of the forward premium over the interest rate differential, $\Delta_t = f_t - s_t + r^f_d - r^f_\$$. The CIP deviation can then be expressed as the difference between dollar and domestic credit spreads. In other words, CIP deviations (measured in a risk-free rate) reflect differences in funding costs across currencies, consistent with evidence in Liao (2020); Rime et al. (2017); Kohler and Müller (2018).

$$\Delta_t = \ell_{\$,t} - \ell_{d,t} + \xi_t - F'(x^D_{\$,t}) \tag{15}$$

I define $R = \left[\begin{array}{cc} y_d - c_d & y_\$ - (\ell_{d,t} + \Delta_t + F'(x^D_{\$,t})) \end{array}\right]^T$. The bank holds an optimal level of dollar and domestic assets that is proportional to the Sharpe ratio of the asset (equation 16). The solution for the optimal allocation of direct and synthetic dollar funding is dependent on whether the bank is in the constrained or unconstrained regions of dollar borrowing (equation 17). Dollar borrowing is similarly defined as a fraction of equity if the bank is constrained, or alternatively the difference between dollar assets and the optimal level of swap funding in the event the bank is unconstrained.

$$\left[\begin{array}{c} A_{d,t} \\ A_{\$,t} \end{array}\right] = \frac{K}{\alpha\sqrt{R^T\Sigma^{-1}R}}\Sigma^{-1}R \tag{16}$$

$$x^D_{\$,t} = \begin{cases} F'^{-1}\left(\ell_\$ - (\ell_d + \Delta)\right) & \xi_t = 0 \text{ [unconstrained]} \\ A_{\$,t} - \gamma K & \xi_t \neq 0 \text{ [constrained]} \end{cases} \tag{17}$$

$$B^D_{\$,t} = \begin{cases} A_{\$,t} - \frac{\ell_\$ - (\ell + \Delta)}{\ell'_d(x^D_{\$,t})} & \xi_t = 0 \text{ [unconstrained]} \\ \gamma K & \xi_t \neq 0 \text{ [constrained]} \end{cases} \tag{18}$$

Equilibrium

In a market of N arbitrageurs, each arbitrageur will receive orders from the bank, $x^D_{j,\$}$, where $\sum_{j=1}^N x^D_{j,\$} = x^D_\$$. Assuming arbitrageurs are symmetric, and have the same risk aversion and capacity to supply dollars in the market. Each arbitrageur supplies an optimal level of dollars x^* determined in equation 4. The arbitrageur acts as a price-setter, and sets the forward price of the swap to absorb bank demands for dollar funding. This gives rise to the following equilibrium for the FX swap market.

Definition [Equilibrium]: *An equilibrium in the FX swap market in period t is characterized by the following:*

1. *arbitrageurs supply $x^*_{\$,t}$ dollars, optimizing mean-variance preferences over wealth (equation 4).*

2. *A representative bank demands $x^D_{\$,t}$ dollars, optimizing the value of their portfolio (equation 17).*

3. *The arbitrageur sets Δ_t such that bank demands for dollar funding are directly met by arbitrageur supply. $x^D_{\$,t}(\Delta_t) = Nx^*_{\$,t}(\Delta_t)$*

Quantitative Easing

To outline the effect of QE, I introduce a parameter M_t which measures an increase in central bank asset purchases.

Definition [Domestic credit spread]: *The domestic credit spread ℓ_d is a function of central bank asset purchases M_t, $\ell_{d,t} = G(M_t)\bar{\ell}_{d,t}$, where $G'(.) < 0$.*

The relationship between central bank asset purchases and the domestic credit spread is consistent with models of preferred habitat imperfect arbitrage in segmented markets Vayanos and Vila (2009); Williamson et al. (2017). Central bank purchases of private sector debt reduce the effective market supply of private debt. Preferred habitat theory suggests that the relative decline in the supply of private bonds raises prices and lowers yields. This compresses domestic credit spreads, defined as the difference between the bond yield and a risk-free rate.[17]

I capture the effects of QE as causing a decline in the domestic credit spread. This creates a wedge between synthetic and direct dollar borrowing costs, causing the bank to reallocate dollar funding toward FX swaps. To absorb excess demand for dollar funding. arbitrageurs raise the premium to swap domestic currency into dollars. A formal statement of the effects of QE is provided in proposition 1.

Proposition 1 [Quantitative Easing]: *Assume the domestic credit spread is $\ell_d = G(M_t)\bar{\ell}_{d,t}$, where $G'(.) < 0$. Define $R = \begin{bmatrix} R_d & R_\$ \end{bmatrix}^T$, where $R_d = y_d - c_d$, $R_\$ = y_\$ - (\ell_{d,t} + r^f_\$ + \Delta_t + F'(x^D_\$))$ are the excess returns on domestic and dollar assets. An unanticipated increase in central bank asset purchases M_t in period 1 leads to:*

1. *A decline in domestic credit spreads ℓ_d, and an increase in $x^D_\$$ to equate synthetic and direct costs of funding.*

2. *In equilibrium, arbitrageurs increase the premium at which domestic currency is swapped into dollars. The CIP deviation widens for banks in both the unconstrained and constrained regions of direct dollar borrowing,*

$$\frac{\partial \Delta}{\partial M} = \begin{cases} -\dfrac{\bar{\ell}_d G'(M)}{1+\frac{NF''(x^D_\$)}{\theta\rho\sigma_s^2}} > 0 & ,\xi_t = 0 \text{ [unconstrained]} \\ -\dfrac{\bar{\ell}_d G'(M)}{1+\frac{NF''(x^D_\$)}{\theta\rho\sigma_s^2} + \frac{N}{\theta\rho\sigma_s^2 A_\$}\left(\frac{1}{\frac{1}{R_\$}+\frac{R_\$}{R^T R}}\right)} > 0 & ,\xi_t \neq 0 \text{ [constrained]} \end{cases}$$

Proof: See Appendix A

[17] Mathematically, let us keep the level of demand for private-sector bonds fixed. Then, a decline in market supply requires a fall in bond yields to induces banks to increase supply to the market.

To further illustrate the effects of QE on bank demands for direct and synthetic dollar funding, Figure 8 characterizes the bank's new equilibrium allocation of dollar funding for varying levels of γ . The threshold γ^* is the boundary at which a bank transitions from the unconstrained to constrained regions of direct dollar borrowing.

$$\gamma^* = \frac{A_\$ - F'^{-1}(\ell_\$ - (\ell_d + \Delta))}{K} \tag{19}$$

The total increase in bank demands for dollar funding after QE is denoted by the area $x^D_{\$,1} - x^D_{\$,0}$. The area $b + c$ in the diagram denotes a reallocation of dollar funding toward FX swaps for banks in the region of unconstrained dollar borrowing, with $\gamma \geq \gamma^*_1$. In contrast, for constrained banks with $\gamma \geq \gamma^*_1$, the channel of increased demand for dollar funding works through QE causing an increase in the excess return on dollar assets. [18] This causes a portfolio rebalancing to hold more dollar assets, which can only be hedged by dollar funding via FX swaps. The increase in synthetic dollar funding by constrained banks is denoted by area a in the Figure.

Negative interest rates

An unanticipated decline in the central bank rate leads to a differential rate of pass-through to loan rates and deposit rates at the zero lower bound. Mathematically, I impose simple functional forms for domestic loan and deposit rates. $y_d = r_m + \mu_A$, and $c_d = min\{0, r_m\}$. This assumes a simple pass-through of the central bank rate to loan rates y_d, which are given at a constant mark-up to the central bank rate equal to μ_A. In contrast, deposit rates are equal to the central bank rate when $r_m > 0$, and is bounded below by zero. I motivate this assumption as a zero lower bound on retail deposit rates, given the incentive for households to prefer holding cash in the event retail deposits go below zero.[19]

A decline in r_m in the region $-\mu_A < r_m < 0$ reduces the excess return on domestic assets. To hedge the dollar asset position, the bank raises its demand for dollars via FX swaps. arbitrageurs absorb the increase in demand by raising the premium banks pay to swap domestic currency into dollars. In the new equilibrium, the bank now has a higher share of dollar assets in its portfolio. This is formally stated in proposition 2.

[18]Recall the excess return on dollar assets is equal to $R_{\$,t} = y_\$ - (\ell_{d,t} + r^f_\$ + \Delta_t + F'(x^D_\$))$. A decline in domestic credit spreads, all else equal, causes a rise in the dollar excess return.

[19]This assumption is validated through a series of empirical papers that document the decline in net interest income in periods of negative interest rates Altavilla et al. (2018); Borio and Gambacorta (2017); Lopez et al. (2018); Claessens et al. (2018). The assumption of differential pass-through to loan and deposit rates has also been used in theoretical banking models Ulate (2018); Brunnermeier and Koby (2016). While these models focus on the general equilibrium effects of negative interest rates on lending and leverage of financial intermediaries, I also document a decline in domestic lending, and a rebalancing to hold more dollar assets.

Proposition 2 [Negative Rates]: *Assume the bank is in the constrained dollar borrowing region, and domestic loan and deposit rates are given by the functions* $y_d = r_m + \mu_A$, $c_d = min\{0, r_m\}$. *Define* $R = \begin{bmatrix} R_d & R_\$ \end{bmatrix}^T$, *where* $R_d = y_d - c_d$, $R_\$ = y_\$ - (\ell_{d,t} + r^f_\$ + \Delta_t + F'(x^D_\$))$ *are the excess returns on domestic and dollar assets. An unanticipated decline in the policy rate* r_m *in the region* $-\mu_A < r_m < 0$ *by the central bank leads to:*

1. *A decline in domestic excess return* R_d*, and a portfolio rebalancing to hold more dollar assets,* $\frac{\partial A_\$}{\partial r_m} = -\frac{R_d A_\$}{R^T R} < 0$. *Consequently, banks increase their hedging demand for dollar funding via FX swaps.*

2. *In equilibrium, arbitrageurs increase the premium at which domestic currency is swapped into dollars. The CIP deviation widens for banks in the constrained region of dollar borrowing,*

$$\frac{\partial \Delta}{\partial r_m} = \begin{cases} 0 & , \xi_t = 0 \text{ [unconstrained]} \\ -\frac{R_d}{\frac{N R^T R}{\rho \theta \sigma^2 A_\$} + \left(1 + \frac{N F''(x^D_\$)}{\theta \rho \sigma^2_s}\right)\left(\frac{R^T R}{R_\$} + R_\$\right)} < 0 & , \xi_t \neq 0 \text{ [constrained]} \end{cases}$$

Proof: See Appendix A

To further illustrate the effects of negative interest rates on bank demands for direct and synthetic dollar funding, Figure 9 characterizes the bank's new equilibrium allocation of dollar funding for varying levels of γ . Negative interest rates reduce the excess return on domestic assets, causing a portfolio rebalancing to hold more dollar assets. Banks in the unconstrained region can fund additional dollar assets by borrowing dollars directly, this is denoted by area $b + c$ in the diagram.[20] In contrast, only constrained banks hedge the additional demand for dollar assets by borrowing dollars synthetically, this increase is denoted by area a.

Model extensions

Swap Lines

I outline a further proposition in Appendix B, in which I discuss central bank swap lines. I show that a swap line provides dollar funding to the bank, but at a penalty to the risk-free rate. In the optimal allocation, the costs of synthetic dollar funding is equal to the cost of obtaining funds via the swap line. A decline in the penalty rate of the swap line, causes a substitution toward dollar funding via the swap line. This reduces demands for dollar funding

[20] In the initial equilibrium, an unconstrained bank has equal costs of direct and synthetic dollar funding, $\underbrace{\ell_{d,t} + \Delta_t + F'(x^D_{\$,t})}_{\text{synthetic dollar cost}} = \underbrace{\ell_{\$,t}}_{\text{direct dollar cost}}$ .Therefore, as synthetic dollar funding cost is convex, $F''(.) > 0$, at the margin, an unconstrained bank will choose direct dollar funding.

in the FX swap market, with a consequent decline in CIP deviations. This supports the results in Bahaj and Reis (2018). They present quantitative evidence of a decline in CIP deviations when the Federal Reserve reduced the penalty rate on swap line borrowings by 50 basis points on November 30, 2011.

Quantitative Exercise

I conduct a simple numerical exercise to test the validity of the model in Appendix C. I estimate the parameters based on setting a pre-crisis CIP deviation of approximately 5 basis points. I calibrate the sensitivity of credit spreads to asset purchases based on estimates of the corporate asset purchase program of the ECB by Abidi et al. (2017). Normalizing the money supply in the pre-crisis to one, I find a widening of CIP deviations by 10 basis points for a doubling of the money base. For perspective, the increase in money base of the ECB during this period from 2007 to 2018 is from \$1.5 Trillion to \$4 Trillion over this period. Based on the model calibration, approximately 20-30 basis point widening of CIP deviations can be attributed to QE. In contrast, the effects of negative interest rates are less pronounced, a negative interest rate of 1% generates a very marginal widening of CIP deviations from 5 to 7.5 basis points. The mute effect of negative rates can be attributed to the given calibration; total dollar assets are relatively insensitive to changes in domestic and dollar returns.

To conclude, the model has provided a rationale for the effects of QE and negative interest rates on the FX swap market. These policies can be viewed as factors affecting bank demands for dollar funding. QE lowers the relative cost of synthetic dollar funding, causing the bank to reallocate dollar funding toward FX swaps. Negative interest rates increase the relative return on dollar assets, causing the bank to increase dollar funding via FX swaps to hedge exchange rate risk.

4 Empirical Evidence

In response to unconventional monetary policies of the Euro area, Japan and Switzerland, the model makes two key predictions. First, as bank demands for dollar funding in the FX swap market increase, arbitrageurs absorb this excess demand by raising the premium at which euros, Swiss francs and yen are swapped into dollars, causing a widening of the CIP deviation. To identify the effects of monetary policy on the CIP deviation, I examine the change in interest rate futures in a high-frequency window around scheduled monetary announcements of the ECB, BOJ and SNB. I document a widening of the cross-currency basis for the euro/\$, yen/\$ and chf/\$ around negative interest rate announcements, and show this effect is robust to CIP deviations at maturities across the term structure.

Second, the model predicts that in response to a decline in domestic credit spreads induced by QE, banks in the Eurozone, Japan and Switzerland substitute toward dollar funding in the FX swap market. Therefore, the share of synthetic dollar funding to total dollar assets should increase. To test this, I use data on interoffice funding of U.S. subsidiaries of banks in the Euro area, Japan and Switzerland as a proxy for the level of synthetic dollar funding. In response to a decline in domestic credit spreads, I document an increase in the share of synthetic dollar funding, all else equal.

Data

Monetary surprises

I use shocks to interest rate futures around scheduled monetary announcements to measure an unanticipated surprise in monetary policy. The identifying assumption is that changes in interest rate futures around announcements is a response to news about monetary policy, and not to other news related to the economy during that period. While the vast majority of the literature deals with computing changes in the Fed funds rate Kuttner (2001); Gurkaynak et al. (2004), I construct an equivalent monetary surprise for the policy rates of the ECB, BOJ and SNB, and use interest rate futures for the 90 day rate. I use 90 day contracts as the equivalent to 1 month contracts of the Federal Reserve policy rate are not available, and have been used as an alternative in other papers Ranaldo and Rossi (2010); Brusa et al. (2016).

Intraday changes Δf_t are calculated as the difference between futures f_t δ^- minutes prior to the meeting and δ^+ minutes after the meeting. I use a wide window 15 minutes prior to the announcement and 45 minutes after the announcement, and extend the wide window 105 minutes after the announcement for the ECB. For the U.S., I scale the change in the interest rate futures based on the specific day of the announcement during the month. [21]A summary of interest rate futures for the central bank policy rate is provided in Table 1. Descriptive statistics for the foreign monetary shocks, including contract length, are provided in Table 2.

$$\Delta f_t = f_{t+\delta^+} - f_{t-\delta^-}$$

CIP Deviation

To calculate CIP deviations based on a LIBOR benchmark, I use the cross-currency basis, which is quoted for cross-currency swaps, obtained from Bloomberg. The cross-currency basis is

[21]The change in implied 30-day futures of the Federal Funds rate $\triangle f1_t$ must be scaled up by a factor related to the number of days in the month affected by the change, equal to $D_0 - d_0$ days, where d_0 is the announcement day of the month, and D_0 is the number of days in that month.

$$MP_t = \frac{D_0}{D_0 - d_0} \Delta f_t$$

available for maturities ranging from 3 months to 30 years. The cross-currency swap is used by the bank as a tool to hedge interest rate risk in foreign currency. Therefore, the bank swas the floating domestic currency LIBOR for fixed, and paying a fixed USD LIBOR to obtain floating LIBOR. The cross-currency basis Δ measures the net cost of engaging in the cross-currency swap, is expressed in equation 20, where $IRS_{\$,t}$ and $IRS_{d,t}$ are the fixed-floating interest rate swaps in USD and domestic currency respectively, and $f - s$ measures the forward premium.[22] A negative Δ indicates that synthetic dollar borrowing costs exceed local borrowing costs.

$$\Delta_t = \underbrace{IRS_{\$,t}}_{\text{direct}} - \underbrace{(IRS_{d,t} + f_t - s_t)}_{\text{synthetic}} \tag{20}$$

The cross-currency basis measures CIP deviations using a LIBOR benchmark. To construct alternative benchmark using Treasury rates, I use a dataset which computes the CIP deviation for Treasuries for a select group of advanced and emerging economies, provided in Du and Schreger (2016); Du et al. (2018b). The CIP deviation now reflects differences in the Treasury yields of dollar and domestic currency, $y_{\$,t}$ and $y_{d,t}$, expressed in equation 21.

$$CIP_t^T = \underbrace{y_{\$,t}^T}_{\text{direct}} - \underbrace{\left(y_{d,t}^T + f_t - s_t\right)}_{\text{synthetic}} \tag{21}$$

Substituting the formula for the forward premium in equation 20, I obtain a formula for the CIP deviation in Treasuries that is a function of Treasury yields, interest rate swap yields, and the cross-currency basis in equation 22. Treasury yields, interest rate swap rates and the cross-currency basis are obtained from Bloomberg.

$$CIP_t^T = y_{\$,t}^T - y_{d,t}^T - (IRS_{\$,t} - \Delta_t - IRS_{d,t}) \tag{22}$$

Credit spreads

Law of one price in bond issuance implies a condition in which the CIP deviation reflects differences in credit spreads across currencies. I define credit spreads as the excess of a corporate bond index over a risk-free rate. In the absence of detailed bank bond issuance, I construct a proxy by taking the difference between a corporate bond index and a risk-free rate at the corresponding maturity. To infer credit spreads, I use corporate bond indices available at Bloomberg, which provide a weighted average over tenors ranging from 1Y to 10Y and credit rating. For a measure of the risk-free rate, I use the interest rate swap at a 5 year maturity. [23]

[22] For swaps at long maturities, the forward market is illiquid. The forward premium can be inferred from the quote of the cross-currency basis Δ. For more details on the cross-currency swap, refer to Figure 4, which is discussed in section 2.

[23] An interest rate swap swaps a fixed for floating interbank rate. Given there is no collateral risk, it is considered a proxy for the risk-free rate in lending currency in the interbank market

Monetary Surprises and CIP Deviations

High frequency response to negative interest rate announcements

First, I examine the high frequency response of the 1 year cross-currency basis around negative interest rate announcements. The relevant interest rates are the deposit facility rate of the ECB, interest rate on current account balances of the BOJ, and the interest rate on sight deposits of the SNB. In each case, the central bank charges a negative rate of interest on reserves financial institutions hold with the central bank.

The ECB made gradual changes to its deposit facility rate. The first announcement was on 5th of June, 2014, in which the deposit facility rate was introduced at -10 basis points. The deposit facility rate was then further reduced to -20 basis points on September 4th, 2014. This was unanticipated by financial markets, and led to a 5 basis point decline in 90 day interest rate futures. The SNB implemented a negative rate on sight balances of 25 basis points on 18th December, 2014.[24] The surprise component of the expansionary announcement led to a 10 basis point decline in interest rate futures. BOJ's interest rate announcement on January 29th, 2016 led to a -10 basis point rate on current accounts with the central bank.[25] This move surprised the market for interest rate projections, leading to a decline of 6 basis points in interest rate futures. In Figure 10, there is compelling evidence of a widening of the CIP deviation for the euro/\$, chf/\$ and yen/\$ in response to the negative rate announcements of the ECB, SNB and BOJ, with full adjustment taking place approximately 2 hours after the policy event window.

High frequency response to QE announcements

Identifying the high frequency impact of QE announcements is difficult, as QE announcements are typically on the details of a program to be implemented at a later date. However, the only example of QE announcements that led to an immediate expansion of the central bank balance sheet are expansions conducted by the SNB in August and September of 2011. The SNB believed the Swiss Franc to be overvalued, and engaged in a large scale purchase of short-term government securities and an accumulation of foreign reserves. This led to a consequent increase in reserves, also known as sight deposits, held at the central bank. The announcements of August 3, August 10 and August 17 of 2011 increased the level of sight deposits from 30B Chf to 80B Chf on August 3rd, which was subsequently increased to 120B Chf on August 10th, and finally 200B Chf on August 17. The SNB then decided to set of a floor of 1.20 Chf per Euro

[24] Press release for SNB announcement: https://www.snb.ch/en/mmr/reference/pre_20141218/source/pre_20141218.en.pdf. In addition to setting the target for sight balances, the SNB maintains a target for 3 month LIBOR to be between -0.75% and 0.25%.

[25] https://www.boj.or.jp/en/announcements/release_2016/k160129a.pdf

on September 6th, and proposed to intervene in FX markets an indefinite amount to maintain the floor. In a detailed account of these policies Christensen et al. (2014), the authors find a cumulative 28 basis point decline in long-term Swiss Confederate bond yields in response to these policies. Examining the cross-currency basis of the Chf/$ around these announcements at a high frequency, there is evidence of a significant widening of deviations shortly after each announcement. Deviations widen by 10 basis points on August 3 and August 10, and by 30 basis points on August 17 (Figure 11).

Monetary surprises: domestic announcements

To more formally test for a contemporaneous response of the cross-currency basis to monetary surprises, I regress daily changes of the cross-currency basis on monetary shocks of the policy rate. The model prediction is that unconventional monetary policy announcements that are based on QE or negative rates should widen the CIP deviation.[26] To test this I use a panel regression discontinuity framework in equation 23. The dependent variable is the daily change in the CIP deviation, $CIP_{i,t} - CIP_{i,t-1}$ for a currency pair (euro/$, chf/$ or yen/$) of a given maturity i. I use maturities $3m, 1Y, 2Y, 3Y, 5Y, 7Y$ and $10Y$, with fixed effects α_i controlling for idiosyncratic demand and supply fundamentals for swaps of a particular maturity. I use an indicator $\mathbb{1}[U_{MPt}]$ for the period of unconventional monetary policy. This specification allows for a different sensitivity of CIP deviations to monetary surprises in the periods of normal and unconventional monetary policy. The coefficient β measures the sensitivity during conventional periods, and $\beta + \gamma$ measures the sensitivity during unconventional periods.

$$CIP_{i,t} - CIP_{it-1} = \alpha_i + \mathbb{1}[U_{MPt}] + \beta MP_t + \gamma \mathbb{1}[U_{MPt}] \times MP_t + u_t \tag{23}$$

I hypothesize that expansionary monetary surprises cause the CIP deviation of the euro/$, chf/$ and yen/$ pairs to become more negative in the regime of unconventional monetary policy. Formally, I test if the effect γ is greater than zero. In contrast, deviations prior to the period of unconventional policy should be unresponsive to monetary policy, $\beta = 0$. The starting date for unconventional monetary policy in Japan is August of 2010. This is when the BOJ introduces its asset purchase program. For the SNB, the relevant starting date is the introduction of a ceiling on the Swiss Franc in August of 2011. In order to prevent an overvalued currency, the SNB intervened in foreign exchange markets by selling Swiss Francs and accumulating foreign reserves. For the ECB, the starting date for unconventional monetary policy is June of 2014. This is when the deposit facility rate first became negative 10 basis points.

I test for the effects on the CIP deviation based on the LIBOR benchmark for the euro/$,

[26] I define the CIP deviation as the difference between the direct and synthetic dollar borrowing rate, which are how deviations are expressed in Figure 1.

chf/\$ and yen/\$ in specifications (1), (2) and (3) of Table 3. LIBOR is the most appropriate benchmark rate to use, given the dollar borrowing premium in the model is reflecting differences between direct and synthetic dollar funding costs in in the interbank market. The coefficient δ measures the net effect of monetary surprises during the period of unconventional monetary policy ($\delta = \beta_\gamma$ based on the specification in equation 23). Based on the regression estimates, the elasticities ranging from 0.5-0.8 for the three pairs with respect to a 1 basis point monetary surprise in the domestic central bank policy rate.

The model makes a prediction about mispricing of the forward premium in response to an excess demand for dollar funding in the FX swap market. If this is so, then this should theoretically affect CIP deviations based on a variety of benchmark rates, not just LIBOR. Therefore, I also test for the effects of monetary surprises on the Treasury basis. In specifications (4) (5) and (6) of Table 3, I test the effects on CIP deviations using a Treasury yield as the benchmark. Consistent with the model prediction, we find quantitatively similar effects on the Treasury CIP deviation, with elasticities ranging from 0.3 to 0.8. This puts forward the argument that it is the common element, the forward premium, that arbitrageurs are adjusting in response to monetary announcements.

Monetary surprises: Federal Reserve announcements

As well as domestic monetary announcements, I also observe that monetary announcements of the Federal Reserve. To measure the effect of U.S. monetary policy surprises, I compute the change in Fed funds futures around scheduled monetary announcements of the Federal Reserve. The period of unconventional monetary policy is characterized by 3 QE programs, which involves purchases of mortgage-backed securities as well as long-term maturities. The dates of QE1, QE2, and QE3, were implemented from December 2008 to March 2010, November 2010 to June 2011, and September 2012 to October 2014 respectively. In particular, the model predicts that QE programs implemented by the Federal Reserve in the period 2008-2012 should have an equal and opposite effect.

Regression results based on the LIBOR and Treasury benchmarks are reported in Table 4. For the LIBOR benchmark in specifications (1), (2) and (3), there is no effect of Federal Reserve monetary surprises on the CIP deviation. In contrast, we find evidence consistent with the model prediction for CIP deviations based on the Treasury benchmark in specifications (4), (5) and (6) in Table 4. The coefficient estimates for the marginal impact of the period of unconventional monetary policy, δ range from from 0.6 to 1.5. The results suggest that following an expansionary QE announcement by the Federal Reserve, there is a narrowing of the Treasury CIP deviation.

In discussing the findings in Table 4, we note that Federal Reserve QE programs of 2008-2012 are public asset purchases, in contrast to private sector purchases of programs implemented by the ECB and BOJ. Therefore, there is little effect of Federal Reserve QE on corporate credit spreads. However, alternative theories of Federal Reserve QE's effects on the CIP deviation in treasuries is found in (Jiang et al., 2018a). Given the Treasury basis measures a relative scarcity of safe assets, an increase in the relative supply of safe assets lowers the convenience yield on US Treasuries–therefore narrowing CIP deviations. This channel is different to the credit channel of private sector QE which works through bank funding costs, and the relative allocation of direct and synthetic dollar funding in the interbank market.

Quantity Effects: Evidence on Bank FX Swap Positions

A testable prediction of the model is that both QE and negative interest rates lead banks in the Eurozone, Japan and Switzerland to substitute toward synthetic dollar funding. Therefore, I expect the fraction of synthetic dollar funding to total dollar assets should increase. While there is no official data on FX swap holdings at a bank level, I use call report data from the Chicago Federal Reserve, which report a large set of balance sheet items of U.S. subsidiaries of foreign (non U.S.) branches.[27] The key variables I use from the call reports are total dollar assets and net flows due to the head office.[28] Interoffice flows measure funding U.S. subsidiaries of foreign (non U.S) banks receive from head quarters. I use this as an approximation of the bank's amount of dollar funding via FX swaps. This is a valid approximation under two assumptions. First, I assume the head quarters of the non U.S. bank only has access to domestic currency funding sources. Second, the U.S. subsidiary's balance sheet only consists of dollar assets. When these conditions are met, all interoffice flows are domestic funding swapped into dollars. [29]

Table 5 documents the share of interoffice funding to total dollar assets for all banks with head quarters in the Euro area, Switzerland, Japan, as well as a set of control countries Australia, Canada and the United Kingdom. The banks are ranked by their average dollar asset position in the period 2014-2017. To examine if there are structural breaks in the share of interoffice flows, I stratify the sample into two periods, 2007-2013, and 2014-2017, and compute the average share of interoffice funding for banks in each period (Table 5). Indeed, interoffice flows as a proportion of total dollar assets is quite high for a set of major non U.S. banks. For example, Deutsche Bank finances up to 60% of its balance sheet of approximately $150 Billion

[27]The relevant form for non-U.S. bank balance sheet items is the FFIEEC 002.

[28]Variable names in call report data are RCFD2944, "Net due to head office and other related institutions in the U.S. and in foreign countries", and RCFD2170, "Total assets".

[29]Even if those assumptions are met, interoffice flows can still be misrepresentative of the actual level of dollar funding the bank obtains via FX swaps. Suppose the bank headquarters directly manages the dollar asset position of the bank. In this case, they can tap into its domestic sources and swap into dollars without requiring the U.S. subsidiary. Second, suppose the U.S. subsidiary can directly issue a domestic currency bond, and can then swap their domestic funding into dollars. In both instances, interoffice flows are an understatement of the true level of dollar funding via FX swaps.

USD through interoffice flows in the period 2014-2017. In contrast, Deutsche only funded 15% of its balance sheet in the former period. Other banks, like Commerzbank and Landesbank, experience a similar trend of relying on interoffice flows to fund its balance sheet in the period 2014-2017.

To formally test for the effect of unconventional monetary policy on the share of synthetic funding, I use the specification in equation 24.The outcome variable is the share of interoffice flows as a proportion of total dollar assets, which I denote S_{ijt}. The U.S. subsidiary j has headquarters in country i, and period t is quarterly.[30] Explanatory variables X_{it} include the difference between the domestic and US dollar risk-free rates, and the domestic corporate credit spread.[31] In the former, I use one month OIS rates obtained from Bloomberg. These rates are a fixed-floating interest rate swap, and are a measure of a risk-free interbank rate. To test for a difference across periods of conventional and unconventional monetary policy, I interact the explanatory variable with U_{MP}, which is equal to 1 for the period in which the central bank implemented negative interest rates or QE. In addition, I incorporate time and bank fixed effects. Time fixed effects control for global or US specific factors, as well as changes in US regulations that may impact the relative trade-off between synthetic and dollar funding. Bank fixed effects absorb idiosyncratic factors such as differences in corporate structure, and bank-specific funding shocks.[32] I choose 2007 as the starting period because it coincides with the beginning of CIP deviations in which systematic differences in direct and synthetic dollar funding costs occur. Prior to 2007, it is likely that the share of dollar assets funded by interoffice flows are largely based on other factors, such as corporate structure and regulation.

$$S_{it} = \alpha_i + \gamma_t + \beta X_{it} + \delta X_{it} \times U_{MP,it} + \epsilon_t \tag{24}$$

The model prediction is that a decline in domestic credit spreads, other things equal, causes a reallocation toward synthetic dollar funding. Likewise, lower domestic interest rates should lead to a portfolio rebalancing to hold more dollar assets, which in turn require more synthetic funding. In particular, the model predicts the effects should be stronger in the period of unconventional monetary policy. I therefore hypothesize that the net effect of unconventional monetary policy, $\beta + \delta$, should be negative. This indicates a decline in domestic interest rates and credit spreads cause a rise in the share of synthetic dollar funding, all else equal.

[30] I aggregate all U.S. branches of bank j, by using the dataset variable RSSD9035, which is the parent ID. In most cases, a bank has most of its dollar assets at the New York branch.

[31] I construct a proxy for the corporate credit spread, using Bloomberg corporate bond indices for a measure of Corporate yields, and the interest rate swap at an equivalent maturity as a measure of the risk-free rate. The credit spread is then computed as the difference between the corporate bond yield and the risk-free rate. See data section for more details on construction.

[32] For example, banks have varying capital requirements and credit ratings. Banks that have varying access to commercial paper markets will cause differences in the fraction of synthetic funding. Some banks may prefer to manage its dollar balance sheet activities at headquarters, in which case interoffice flows are negligible.

Results for U.S. subsidiaries with head quarters in the Euro area, Japan and Switzerland support these predictions (Table 6). In specification 1, a 100 basis point decline in the domestic OIS rate, all else equal, increases the share of synthetic dollar funding by 10 percentage points. In specification 2, a decline in credit spreads has a similar quantitative effect. However, the net effect of credit spreads in the period of unconventional monetary policy is much higher. A 100 basis point decline in domestic credit spreads increases the share of synthetic funding by approximately 20 basis points during this period. The higher sensitivity of synthetic dollar funding to credit spreads during the period of QE policies is consistent with the model. This is precisely the time during which domestic credit spreads were compressed. This in turn leads to a decline in the relative cost of synthetic dollar funding and a substitution toward dollar funding via FX swaps.

A relevant concern with the specification is the endogeneity of domestic credit spreads. Consider a bank subject to a domestic funding shock, in which funding in domestic interbank markets becomes scarce. This shock can cause both a rise in domestic credit spreads, and a decline in the share of synthetic dollar funding as headquarters is less able to provide funding. To address endogeneity, I use the lagged relative growth of the domestic central bank balance sheet as an instrument for domestic credit spreads. The identifying assumption is that QE affects the share of synthetic dollar funding solely through causing domestic credit spreads to decline, and second, I use lagged central bank balance sheet as it is plausibly exogenous to domestic funding shocks in the current period. Specification 3 uses the instrument for credit spreads, and find an increase in the effect of credit spreads on the synthetic funding share over the entire period.

I conduct regressions for a set of banks with headquarters in control countries of Australia, Canada and the UK. These countries did not practice unconventional monetary policy, and so the model predicts that it is a relevant benchmark with which to compare the effects. In specifications 4 and 5, I find there is no significant effect of interest rates and credit spreads on the share of synthetic dollar funding for these banks.

5 Conclusion

One of the central tenets of international finance is covered interest rate parity, an arbitrage condition that has been consistently violated since the financial crisis of 2008. Initial deviations were due to rises in default risk in interbank markets. But since 2014, rationalizing the consistent violation of an arbitrage condition is difficult, given that default risk in interbank markets has returned to pre-crisis levels, and that the pairs for which deviations are widest, the euro/\$, yen/\$ and chf/\$, are traded in especially deep and liquid markets.

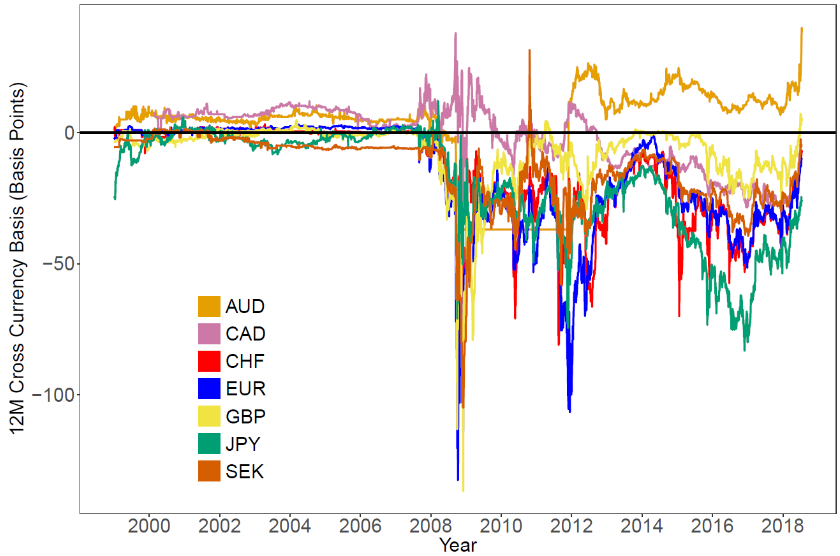
I propose a theory in which the unconventional monetary policies of the ECB, BOJ and SNB are the key factor explaining the persistence of CIP deviations. I model QE as central bank purchases of privately-issued debt. In reducing the market supply of privately-issued debt, QE compresses domestic credit spreads. This reduces the cost of swapping euros, Swiss francs and yen into dollars. Banks therefore reallocate dollar funding toward FX swaps. Negative interest rates for their part cause a relative decline in domestic asset returns. This induces banks to rebalance their portfolios toward dollar assets, which in turn are funded by obtaining dollars via FX swaps. Both policies therefore increase bank demands for swapping euros, Swiss francs and yen into dollars. arbitrageurs, who are intermediaries that take the other end of the FX swap, supply dollars in exchange for those currencies. Because arbitrageurs are risk averse, they face balance sheet risk proportional to the size of the swap position. To absorb the excess demand for dollar funding, they therefore raise the premium at which banks swap domestic currency into dollars, widening the CIP deviation.

I then provide empirical evidence to support the predictions of the model. First, I observe a significant widening of the CIP deviations for the euro/$, yen/$ and chf/$ around the negative interest rate and QE announcements. The model also predicts, in response to a decline in domestic credit spreads induced by QE, a rise in bank demands for dollar funding. Using interoffice flows from call reports, I proxy for holdings of FX swaps by U.S. subsidiaries of banks in the Euro area, Japan and Switzerland. Consistent with the model, I document a rise in the share of synthetic dollar funding (sourced via FX swaps) to total dollar assets in response to a decline in domestic credit spreads.

This paper has implications for policy and suggestions for future work. First, CIP deviations can be interpreted as a tax on dollar funding for non U.S. banks. While a deviation of 50 basis points may be small, the daily turnover in FX swap markets amounts to $ 3 Trillion, and pairs of the euro/$ and yen/$ account for almost half of the turnover in all FX swaps. This suggests a sizable hedging cost to bank balance sheets that may cause inefficiencies in the bank's portfolio and erode bank profits. This implication can be tested formally using data. If verified the policy implications will need to be taken on board by policy makers concerned with the profitability and stability of their banking systems. All of this suggests that to the extent unconventional monetary policies of the Eurozone, Japan and Switzerland remain, there will be a structural imbalance in bank demands for dollar funding in the FX swap market. This means CIP deviations will continue to persist. This naturally implies that a tapering of the balance sheet by the ECB, BOJ and SNB, combined with a return to positive interest rates, is necessary for CIP to hold.

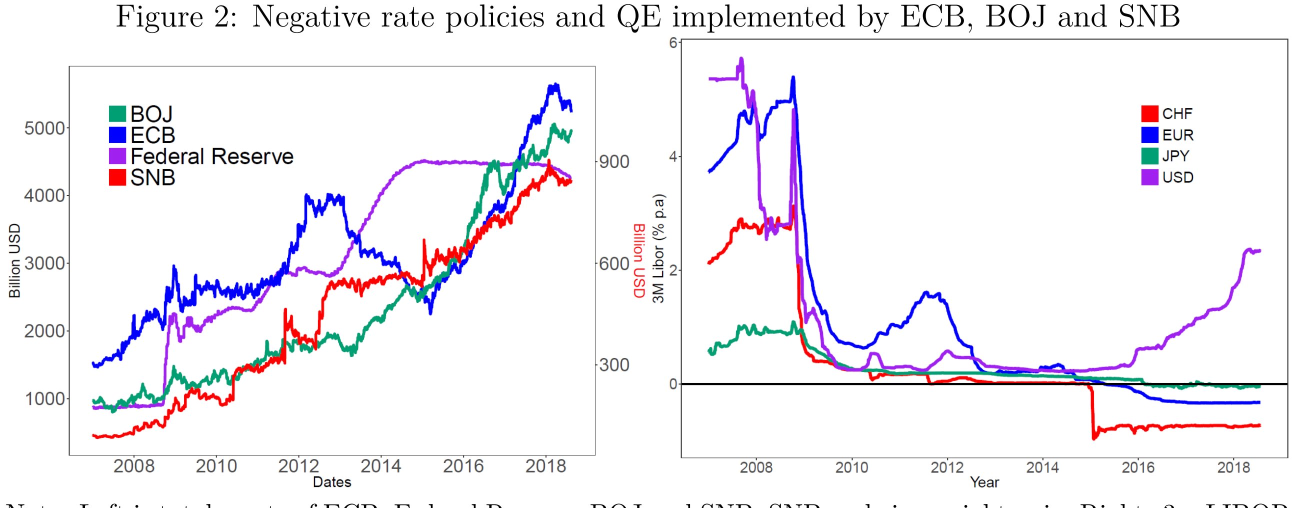
Figures

Figure 1: The puzzle of persistent CIP deviations



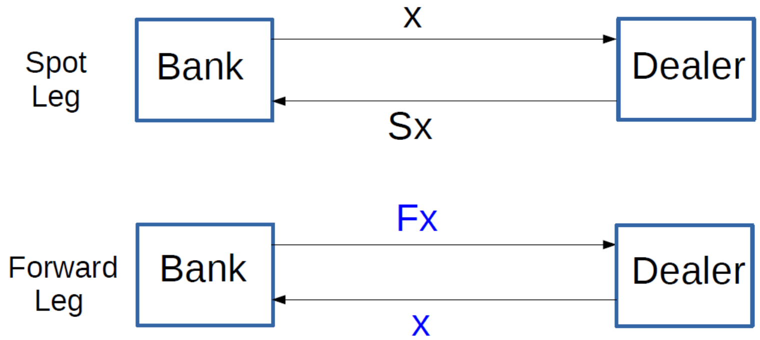
Note: 12M CIP deviation measured in basis points, obtained from Bloomberg. This provides a measure of CIP deviations based on a LIBOR benchmark rate. Deviations are defined as the difference between the direct dollar borrowing rate and the synthetic dollar borrowing rate, which is the cost of borrowing in the domestic currency, and then swapping into dollars through the FX swap market. Negative deviations indicate a dollar borrowing premium for the euro/$, chf/$ and yen/$ pairs.

Figure 2: Negative rate policies and QE implemented by ECB, BOJ and SNB



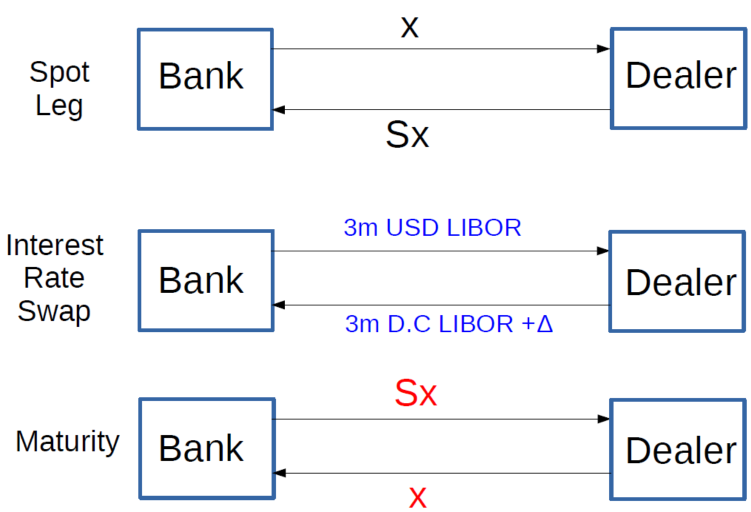
Note: Left is total assets of ECB, Federal Reserve, BOJ and SNB. SNB scale is on right-axis. Right: 3m LIBOR rates from Bloomberg.

Figure 3: Foreign exchange swap



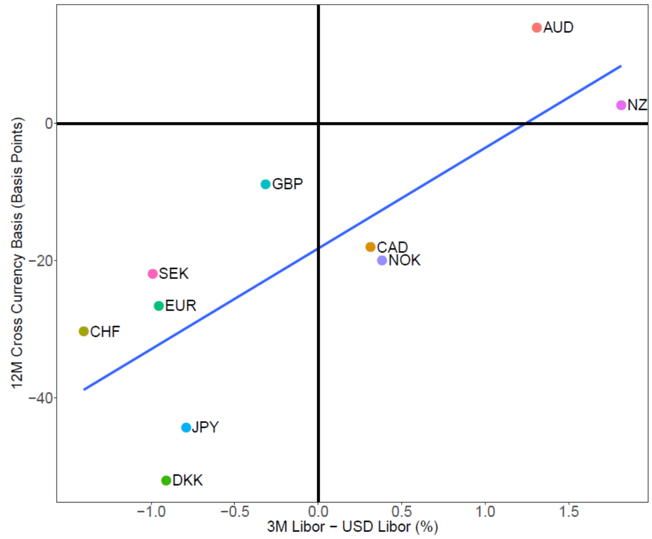
Note: FX swap is typically for maturities at less than 3m. At the spot leg, domestic currency and dollars are swapped at the prevailing spot rate. At maturity, the principals are then re-exchanged at the forward rate.

Figure 4: Cross-currency swap



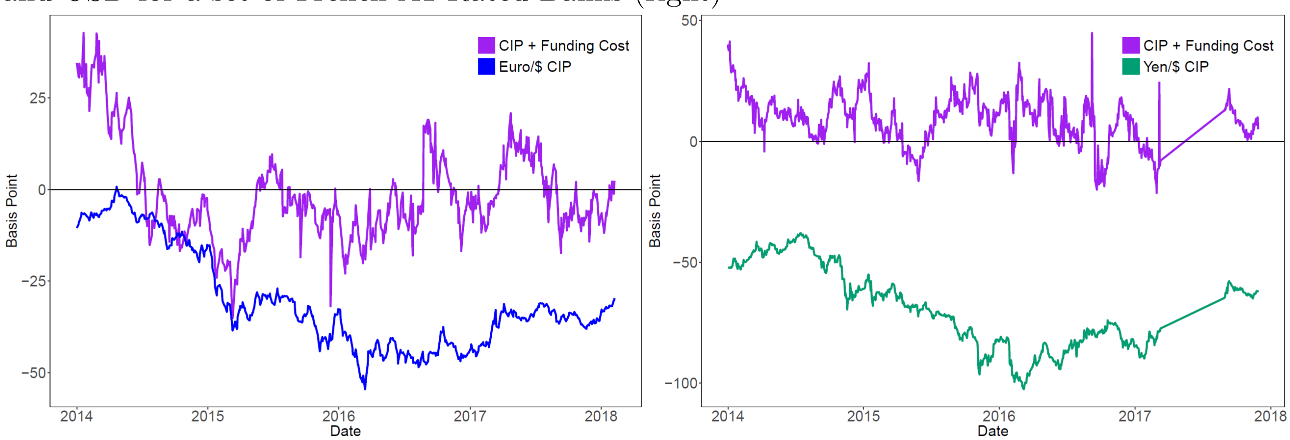
Note: The Cross-Currency Swap is typically for maturities >3m. In the spot leg, dollars are exchanged at spot. The bank and dealer then engages in an interest rate swap, in which the bank pays 3m USD LIBOR, and the dealer pays 3m LIBOR in domestic currency with the addition of the cross-currency basis Δ. At maturity the principals are re-exchanged at the initial spot rate.

Figure 5: CIP Deviations and LIBOR interest rate differential, advanced economies, 2014-present



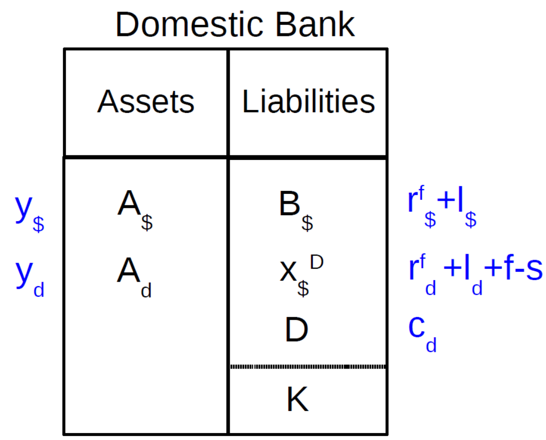
Note: This plot takes the average of the cross-currency basis and LIBOR interest rate differential in the period since 2014. CIP deviation is with respect to USD. Source: Bloomberg

Figure 6: Credit Spreads in Yen and USD for a set of Japan A1 Rated Banks (left) and Euros and USD for a set of French A1 Rated Banks (right)



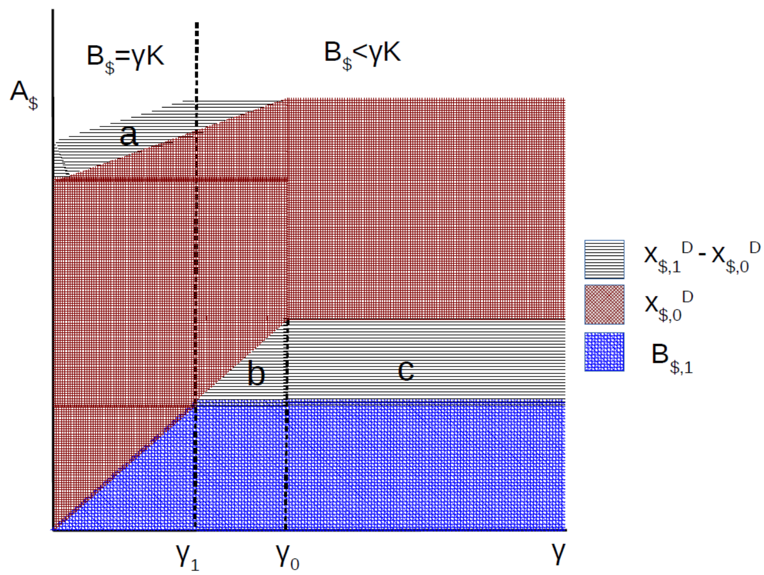
Note: This is a plot showing CIP deviations for the euro/$ (left) and yen/$ deviations, as well as a measure that takes into account funding costs across currencies. The CIP deviation used is the 5 year CIP deviation.

Figure 7: Bank Balance Sheet



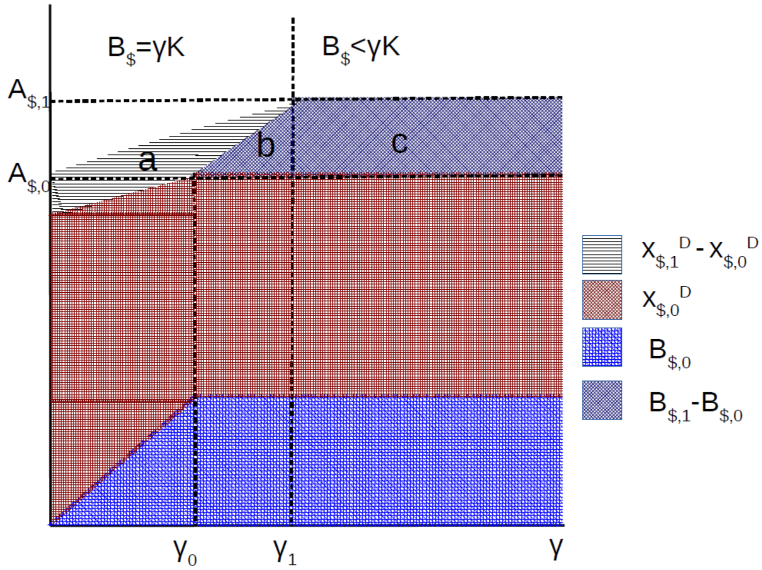
Note: This Figure illustrates a stylized balance sheet of a domestic bank with equity K. On the asset side, the bank invests in domestic and dollar assets A_d and $A_\$$, with returns y_d and $y_\$$ respectively. They fund their balance sheet with domestic deposits D with cost c_d. They have two sources of dollar funding. Direct dollar borrowing $B_\$$ with cost $r^f_\$ + l_\$$, which is the cost of issuing a dollar bond, decomposed into the risk-free rate and the dollar credit spread. Synthetic dollar borrowings via FX swaps $x^D_\$$, with cost $r^f_d + l_d + f - s$. This is the cost of issuing a domestic bond, which is then swapped into dollars based on the forward premium $f - s$.

Figure 8: Allocation of direct and synthetic dollar funding sources for banks with varying γ. Both initial and final equilibrium after QE is shown.



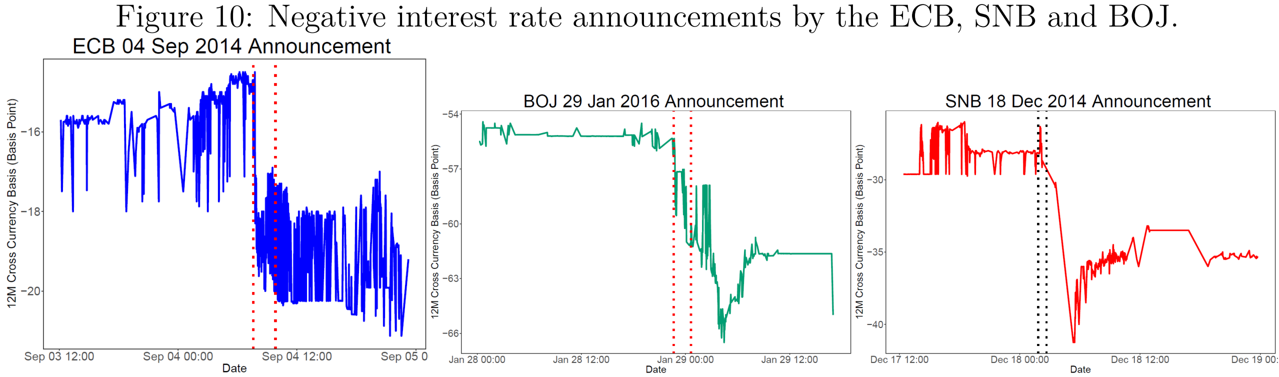
Note: This schematic illustrates the effects of QE on the allocation of direct and synthetic dollar funding. For a bank that is not dollar constrained, with $\gamma > \gamma_1$, they increase their demands for synthetic dollar funding. This is denoted by areas b and c. For banks that are constrained in dollar borrowing, with $\gamma < \gamma_1$, there is also a substitution toward synthetic funding as well, given by area a.

Figure 9: Allocation of direct and synthetic dollar funding sources for banks with varying γ. Both initial and final equilibrium after negative rates is shown.



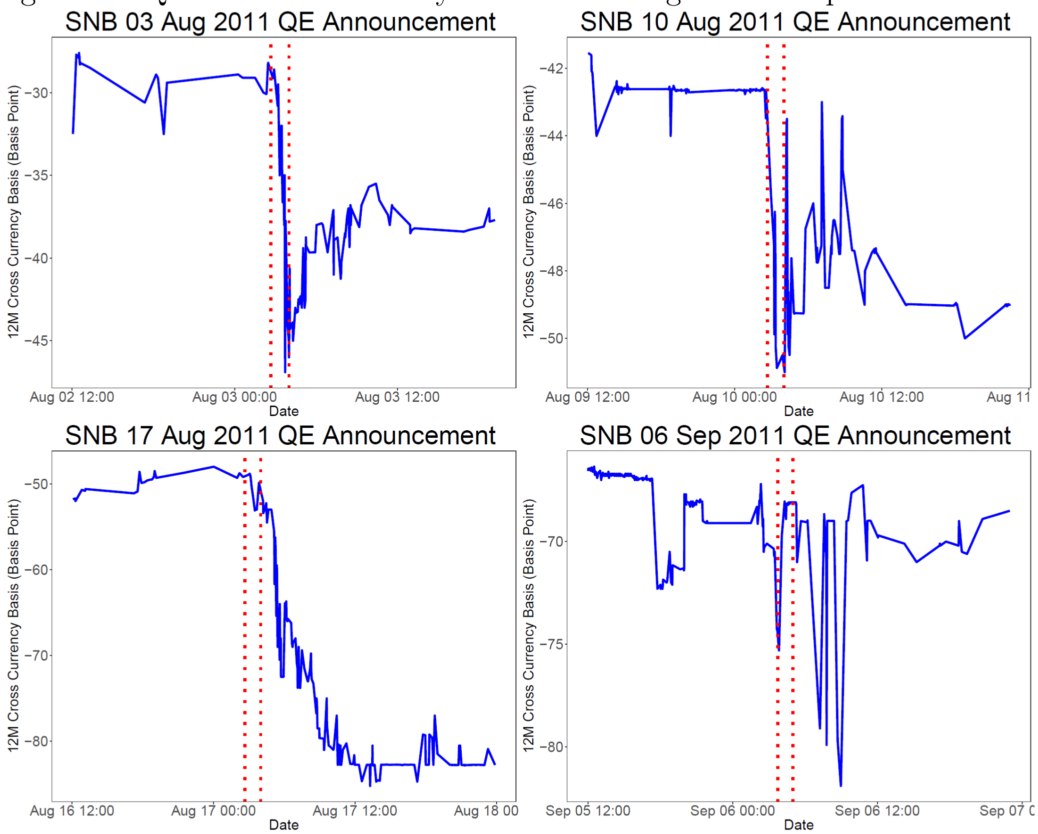
Note: This schematic illustrates the effects of negative interest rates on the allocation of direct and synthetic dollar funding. For a bank that is not dollar constrained, with $\gamma > \gamma_1$, the increase in dollar assets is funded entirely by an increase in direct dollar borrowing. This is denoted by area c. For banks that are constrained in direct dollar borrowing, with $\gamma < \gamma_0$, the increase in dollar assets is met by an increase in synthetic dollar funding, denoted by area a. For banks that are partially constrained, with $\gamma_0 < \gamma < \gamma_1$, the increase in dollar assets is funded by both direct and synthetic sources.

Figure 10: Negative interest rate announcements by the ECB, SNB and BOJ.



Note: Response of 12m CIP deviation of the euro/\$, chf/\$ and yen/\$ to negative interest rate announcements by the ECB, SNB and BOJ respectively. Source: Thomson Reuters Tick History

Figure 11: QE announcements by the SNB in August and September of 2011



Note: Response of 12m CIP deviation of the chf/\$ around key announcements of the SNB in August and September of 2011. Source: Thomson Reuters Tick History

Tables

Table 1: Underlying interest rate futures to measure monetary shocks

Central Bank	Underlying policy rate	Monetary shock
ECB	EUREX 3-Month Euribor	$MP_{EU,t} = \Delta f1^{surprise}_{EU,t}$
BOJ	TFX (TIFFE) 3-Month Euroyen Tibor	$MP_{JPY,t} = \Delta f1^{surprise}_{JPY,t}$
SNB	LIFFE 3-Month Euroswiss Franc	$MP_{SWZ,t} = \Delta f1^{surprise}_{SWZ,t}$
Federal Reserve	Fed Funds Rate futures 1-Month	$\mathrm{MP}_{US,t} = \frac{D_0}{D_0 - d_0}\Delta f_t$

Note: This table lists the interest rate futures of the underlying central bank rate for the central banks ECB, BOJ, SNB and Federal Reserve. Source for interest rate futures is CQG Financial Data. For non-U.S. central banks, the 90 day rate is used. For the U.S. the immediate 1 month futures is used, and therefore the monetary surprise is multiplied by the scaling factor $\frac{D_0}{D_0 - d_0}$, where D_0 is the number of days in the month of the FOMC meeting, and d_0 is the day of the meeting within the month.

Table 2: Descriptive statistics, monetary shocks

	Mean	SD	p-5	p-25	p-50	p-75	p-95	Obs	Contract Period
$MP1_{\mathrm{US}}$	-0.012	0.076	-0.121	-0.010	0.000	0.040	0.210	168	07/95 - 09/16
MP_{SWZ}	-0.029	0.101	-0.180	-0.060	-0.010	0.010	0.080	90	02/91 - 09/16
MP_{UK}	-0.006	0.063	-0.090	-0.020	0.000	0.010	0.080	232	06/97 - 09/16
MP_{EU}	0.001	0.042	-0.060	-0.015	0.000	0.020	0.068	240	01/99 - 09/16

All values in percentage points

Table 3: Response of Euro/$, Chf/$ and Yen/$ CIP Deviations to ECB, SNB and BOJ Monetary Announcements

	(1)	(2)	(3)	(4)	(5)	(6)
	Libor basis			Treasury Basis		
	eur/usd	chf/usd	yen/usd	eur/usd	chf/usd	yen/usd
MP	-0.086	0.154	-1.055	0.080	0.198	-1.434
	(0.048)	(0.044)***	(0.461)*	(0.058)	(0.045)***	(0.584)*
MP $\times$ $\mathbb{1}[U_{\mathrm{MP}}]$	0.652	0.466	1.826	0.238	0.448	2.207
	(0.123)***	(0.161)**	(0.529)***	(0.145)	(0.164)**	(0.669)***
δ	0.566	0.620	0.772	0.318	0.646	0.774
	(.113)***	(.155)***	(.258)***	(.133)**	(.157)***	(.326)**
R^2	0.049	0.125	0.027	0.011	0.097	0.013
observations	599	241	704	854	350	1001

*** p<0.01, ** p<0.05 *p<0.1, robust standard errors in parantheses.

Note: This table regresses the change in the Libor and Treasury CIP deviation on monetary surprises of domestic central banks. For the euro/$ pair, we use monetary surprises of the ECB based on 90 day futures. For the chf/$ pair, we use monetary surprises of the SNB. For the yen/$ pair, we use monetary surprises of the BOJ. The LIBOR basis is the CIP deviation measured based on LIBOR, and is obtained from Bloomberg. The Treasury basis is the CIP deviation measured based on Treasury yields, and is obtained from Du et al. (2018b). CIP deviations are calculated for maturities ranging from 3 months to 10 year tenor. an announcement on day t, the daily change is computed as the difference between the end of day price on days t and $t-1$. The monetary shock is computed as the change in interest rate futures computed within a wide window around the monetary announcement. The indicator $\mathbb{1}[U_{\mathrm{MP}}]$ takes a value of one when the central bank practices unconventional monetary policy. The marginal effect of the period of unconventional monetary policy is captured by δ, which is the sum of the coefficients on MP and $MP \times \mathbb{1}[U_{\mathrm{MP}}]$. Sample period is from 01/2006 to 12/2016.

Table 4: Response of Euro/\$, Chf/\$ and Yen/\$ CIP Deviations to Federal Reserve Announcements

	(1)	(2)	(3)	(4)	(5)	(6)
	Libor basis			Treasury Basis		
	eur/usd	chf/usd	jpy/usd	eur/usd	chf/usd	jpy/usd
MP	-0.105	-0.058	-0.059	-0.967	-0.227	-0.798
	(0.044)*	(0.045)	(0.047)	(0.117)***	(0.080)**	(0.104)***
MP $\times$ $\mathbb{1}[U_{\mathrm{MP}}]$	0.010	0.303	-0.163	-0.625	-0.348	-0.256
	(0.108)	(0.112)**	(0.117)	(0.289)*	(0.197)	(0.258)
δ	-0.095	0.245	-0.222	-1.592	-0.575	-1.054
	(.099)	(.102)**	(.107)	(.265)***	(.18)***	(.236)***
R^2	0.017	0.026	0.015	0.164	0.038	0.124
observations	404	397	405	567	567	567

*** p<0.01, ** p<0.05 *p<0.1, robust standard errors in parantheses.

Note: This table regresses the change in the Libor and Treasury CIP deviation on monetary surprises of the Federal Reserve. For monetary surprises, we use the change in the nearest month Federal Fund Futures around scheduled monetary announcements. The LIBOR basis is the CIP deviation measured based on LIBOR, and is obtained from Bloomberg. The Treasury basis is the CIP deviation measured based on Treasury yields, and is obtained from Du et al. (2018b). CIP deviations are calculated for maturities ranging from 3 months to 10 year tenor. an announcement on day t, the daily change is computed as the difference between the end of day price on days t and $t-1$. The monetary shock is computed as the change in interest rate futures computed within a wide window around the monetary announcement. The indicator $\mathbb{1}[U_{\mathrm{MP}}]$ takes a value of one when the central bank practices unconventional monetary policy. The marginal effect of the period of unconventional monetary policy is captured by δ, which is the sum of the coefficients on MP and $MP \times \mathbb{1}[U_{\mathrm{MP}}]$. Sample period is from 01/2006 to 12/2016.

Table 5: Share of Interoffice Funding to Total Dollar Assets, Call Reports

Bank	Region	2007-2013 $A_\$$	2007-2013 $\frac{x_\$}{A_\$}$	2014-2017 $A_\$$	2014-2017 $\frac{x_\$}{A_\$}$
DEUTSCHE BK AG	EUR	$145.8 B	0.13	$156.9 B	0.51
BANK TOK-MIT UFJ	JPY	$88.6 B	0.17	$148.1 B	0.15
BANK OF NOVA SCOTIA	CAD	$101.8 B	0.27	$142.6 B	0.21
NORINCHUKIN BK	JPY	$75.7 B	0.00	$123.7 B	0.00
SUMITOMO MITSUI BKG	JPY	$58.7 B	0.26	$110.4 B	0.12
SOCIETE GENERALE	EUR	$84.1 B	0.08	$76.6 B	0.11
CREDIT SUISSE	CHF	$57.3 B	0.02	$68.9 B	0.00
RABOBANK NEDERLAND	EUR	$74.8 B	0.02	$57 B	0.05
STANDARD CHARTERED BK	GBP	$30.4 B	0.09	$53.2 B	0.16
TORONTO-DOMINION BK	CAD	$40.9 B	0.00	$52.1 B	0.00
NORDEA BK FINLAND PLC	EUR	$26.8 B	0.06	$37.1 B	0.22
DEXIA CREDIT LOCAL	EUR	$41.8 B	0.12	$32.5 B	0.11
NATIONAL AUSTRALIA BK	AUD	$20.7 B	0.02	$25.5 B	0.02
AUSTRALIA & NEW ZEALAND	AUD	$10.7 B	0.26	$21.9 B	0.02
MITSUBISHI UFJ TR & BKG	JPY	$11.5 B	0.04	$21.1 B	0.08
LANDESBK BADEN WUERTTEMB	EUR	$11.5 B	0.22	$18.2 B	0.05
LLOYDS TSB BK PLC	GBP	$24.3 B	0.14	$17 B	0.31
COMMONWEALTH BK OF AUS	AUD	$8 B	0.00	$16.2 B	0.00
DZ BK AG DEUTSCHE ZENTRA	EUR	$8.8 B	0.00	$14.7 B	0.01
WESTPAC BKG CORP	AUD	$15.4 B	0.02	$13.7 B	0.06
BAYERISCHE LANDESBANK	EUR	$19.8 B	0.34	$11.2 B	0.19
CREDIT INDUS ET CMRL	EUR	$11.9 B	0.17	$10.7 B	0.27
NATIONAL BK OF CANADA	CAD	$12 B	0.00	$10.1 B	0.10
LANDESBANK HESSEN-THURIN	EUR	$11.5 B	0.65	$9.4 B	0.65
COMMERZBANK AG	EUR	$14.2 B	0.37	$6.5 B	0.55
BANCO BILBAO VIZCAYA ARG	EUR	$20.3 B	0.18	$5.2 B	0.16
KBC BANK NV	EUR	$8 B	0.31	$4.7 B	0.16
NORDDEUTSCHE LANDESBANK	EUR	$5.7 B	0.13	$4.2 B	0.45
HSH NORDBK AG	EUR	$10.3 B	0.49	$3.8 B	0.77
SHOKO CHUKIN BK	JPY	$0.6 B	0.73	$0.7 B	0.26
ALLIED IRISH BKS	EUR	$4.3 B	0.32	$0.7 B	0.63
BANCA MONTE DEI PASCHI	EUR	$1.3 B	0.00	$0.5 B	0.07
BANCO ESPIRITO SANTO	EUR	$0.1 B	0.77	$0.2 B	0.92

Note: This table reports total dollar assets, $A_\$$, and the share of interoffice flows to total dollar assets, $\frac{x_\$}{A_\$}$, for U.S. branches of foreign (non U.S.) banks. Data is obtained from the FFIEEC 002 form and Call Reports of Chicago Federal Reserve. Reported data are averages taken over periods 2007-2013 and 2014-2017, and excludes banks which do not have data for both periods. Dollar assets are quoted in Billions of USD. Country labels indicate the currency of domicile of the parent bank. EUR=Euro Zone, JPY=Japan, CHF=Switzerland, AUD=Australia, CAD=Canada, GBP=United Kingdom.

Table 6: Determinants of the fraction of synthetic dollar funding for U.S. subsidiaries of European, Japanese and Swiss banks

	(1)	(2)	(3)	(4)	(5)
	S_{ijt}	S_{ijt}	S_{ijt}	S_{ijt}	S_{ijt}
$i_{d,ois} - i_{\$,ois}$	-0.0928***			-0.0474	
	(0.0333)			(0.0316)	
$i_{d,ois} - i_{\$,ois} \times \mathbb{1}[U_{\mathrm{MP}}]$	0.0127				
	(0.272)				
cs_d		-0.0983***	-0.133***		-0.0454
		(0.0257)	(0.0403)		(0.0340)
$\mathrm{cs}_d \times \mathbb{1}[U_{\mathrm{MP}}]$		-0.111*	-0.0803		
		(0.0582)	(0.0980)		
Constant	0.156***	0.252***	0.147**	0.210	0.351*
	(0.0442)	(0.0725)	(0.0658)	(0.151)	(0.185)
Observations	2,379	2,460	2,011	759	775
Number of bankid	39	39	39	12	12
Country Group	Treatment	Treatment	Treatment	Control	Control
Bank FE	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes
Year Quarter FE	Yes	Yes	Yes	Yes	Yes
IV	No	No	Yes	No	No

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Note: This table regresses the fraction of synthetic dollar funding to total dollar assets, using Chicago Federal Reserve Call Reports. Data is obtained from the FFIEEC 002 form requiring foreign subsidiaries of non U.S. banks to report their balance sheet activities. Dependent variable is then calculated as the ratio of interoffice flows to total dollar assets. Standard errors are clustered at the bank level, and data is quarterly and starts in 2007. Explanatory variables include the interest rate differential, which is the domestic OIS rate less the USD OIS rate, and the domestic credit spread, which is calculated as the difference between the corporate and government bond index at all tenors. Interest rates and bond indices are obtained from Bloomberg.

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6 Appendices

A: Model Proofs

Proof of Proposition 1: QE

Unconstrained Bank

From equation 17, an unconstrained bank has $\xi_t = 0$. The first order condition can then be rewritten as follows. Note that we drop time subscripts as the equilibrium is static.

$$F'(x_\$^D) = \ell_\$ - (\bar{\ell}_d G(M) + \Delta) \tag{6.25}$$

In equilibrium, arbitrageurs set a price Δ such that in equilibrium, $x_\$^D = N\frac{\Delta}{\rho\theta^2\sigma_s^2}$. Taking the derivative of equation 6.25 with respect to M,

$$F''(x_\$^D)N\frac{\Delta}{\rho\theta^2\sigma_s^2}\frac{\partial\Delta}{\partial M} = -\bar{\ell}_d G'(M) - \frac{\partial\Delta}{\partial M} \tag{6.26}$$

Rearranging terms, I obtain an expression for the effect of central bank asset purchases M on the equilibrium CIP deviation..

$$\frac{\partial\Delta}{\partial M} = -\frac{\bar{\ell}_d G'(M)}{1 + \frac{NF''(x_\$^D)}{\rho\theta^2\sigma_s^2}} > 0 \tag{6.27}$$

Constrained Bank

The effects on a constrained bank is different. Now, bank demands for dollar funding are given by $x_\$^D = A_\$ - \gamma K$. In equilibrium, $x_\$^D = N\frac{\Delta}{\theta\rho\sigma_s^2}$.

$$N\frac{\Delta}{\rho\theta^2\sigma_s^2} = A_\$ - \gamma K \tag{6.28}$$

Taking derivative with respect to M,

$$\frac{N}{\theta\rho\sigma_s^2}\frac{\partial\Delta}{\partial M} = \frac{\partial A_\$}{\partial M} + \frac{\partial A_\$}{\partial\Delta}\frac{\partial\Delta}{\partial M} \tag{6.29}$$

Rearranging terms, I obtain an expression for the effect of central bank asset purchases M on the equilibrium CIP deviation.

$$\frac{\partial\Delta}{\partial M} = \frac{\frac{\partial A_\$}{\partial M}}{\frac{N}{\rho\theta^2\sigma_s^2} - \frac{\partial A_\$}{\partial\Delta}} \tag{6.30}$$

To simplify the notation, denote $A_\$ = \frac{K}{\alpha}\frac{R_\$}{(R^T\Sigma R)^{\frac{1}{2}}}$, where $R = \begin{bmatrix} R_d & R_\$ \end{bmatrix}^T$.$R_d$ is the domestic excess return $y_d - c_d$, and $R_\$$ is the dollar excess return $y_\$ - (l_d + r^f_\$ + \Delta + F'(x^D_\$))$. Σ is the covariance matrix of returns, and for tractability, I assume $\Sigma = I_{2\times 2}$. Solving for the derivatives $\frac{\partial A_\$}{\partial M}$ and $\frac{\partial A_\$}{\partial \Delta}$, we obtain,

$$\frac{\partial A_\$}{\partial M} = -\bar{\ell}_d G'(M) A_\$ \left(\frac{1}{R_\$} + \frac{R_\$}{R^T R} \right) \tag{6.31}$$

$$\frac{\partial A_\$}{\partial \Delta} = -\left(1 + \frac{N F''(x^D_\$)}{\rho\theta^2\sigma_s^2} \right) A_\$ \left(\frac{1}{R_\$} + \frac{R_\$}{R^T R} \right) \tag{6.32}$$

Finally, substituting the expressions for $\frac{\partial A_\$}{\partial M}$ and $\frac{\partial A_\$}{\partial \Delta}$ gives the analytical solution for $\frac{\partial \Delta}{\partial M}$

$$\frac{\partial \Delta}{\partial M} = -\frac{\bar{\ell}_d G'(M)}{1 + \frac{N F''(x^D_\$)}{\rho\theta^2\sigma_s^2} + \frac{N}{\rho\theta^2\sigma_s^2 A_\$}\left(\frac{1}{\frac{1}{R_\$} + \frac{R_\$}{R^T R}} \right)} > 0 \tag{6.33}$$

Proof of Proposition 2: Negative interest rates

Constrained Bank

Bank demands for dollar funding are given by $x^D_\$ = A_\$ - \gamma K$. In equilibrium, $x^D_\$ = N\frac{\Delta}{\theta\rho\sigma_s^2}$.

$$N\frac{\Delta}{\rho\theta^2\sigma_s^2} = A_\$ - \gamma K \tag{6.34}$$

Taking the derivative with respect to r_m,

$$\frac{N}{\theta\rho\sigma_s^2}\frac{\partial \Delta}{\partial r_m} = \frac{\partial A_\$}{\partial r_m} + \frac{\partial A_\$}{\partial r_m}\frac{\partial \Delta}{\partial r_m} \tag{6.35}$$

Rearranging terms, I obtain an expression for the effect of central bank asset purchases r_m on the equilibrium CIP deviation.

$$\frac{\partial \Delta}{\partial r_m} = \frac{\frac{\partial A_\$}{\partial r_m}}{\frac{N}{\rho\theta^2\sigma_s^2} - \frac{\partial A_\$}{\partial \Delta}} \tag{6.36}$$

Similar to analyzing the effects of QE on a central bank, lets simplify the notation. Denote $A_\$ = \frac{K}{\alpha}\frac{R_\$}{(R^T\Sigma R)^{\frac{1}{2}}}$, where $R = \begin{bmatrix} R_d & R_\$ \end{bmatrix}^T$.$R_d$ is the domestic excess return $y_d - c_d$, and $R_\$$ is the dollar excess return $y_\$ - (l_d + r^f_\$ + \Delta + F'(x^D_\$))$. Σ is the covariance matrix of returns, and for tractability, I assume $\Sigma = I_{2\times 2}$. Solving for the derivatives $\frac{\partial A_\$}{\partial M}$ and $\frac{\partial A_\$}{\partial \Delta}$, we obtain:

$$\frac{\partial A_\$}{\partial r_m} = -\frac{R_d A_\$}{R^T R} \tag{6.37}$$

$$\frac{\partial A_\$}{\partial \Delta} = -\left(1 + \frac{NF''(x_\$^D)}{\rho\theta^2\sigma_s^2}\right) A_\$ \left(\frac{1}{R_\$} + \frac{R_\$}{R^T R}\right) \tag{6.38}$$

Finally, substituting the expressions for $\frac{\partial A_\$}{\partial r_m}$ and $\frac{\partial A_\$}{\partial \Delta}$ gives the analytical solution for $\frac{\partial \Delta}{\partial r_m}$

$$\frac{\partial \Delta}{\partial r_m} = -\frac{R_d}{\frac{NR^T R}{\rho\theta^2\sigma^2 A_\$} + \left(1 + \frac{NF''(x_\$^D)}{\rho\theta^2\sigma_s^2}\right)\left(\frac{R^T R}{R_\$} + R_\$\right)} \tag{6.39}$$

B: Model extension: Central Bank Swap Lines

Proposition 3 [Swap Lines]: *Assume the bank operates in the constrained dollar borrowing region, and the bank is facing a crisis in dollar borrowing, $B_\$ \leq (\gamma - \psi)K$. Assume that in response to the crisis in dollar borrowing, the central bank extends dollar funding via a swap line with the Federal Reserve. This leads to:*

1. *A substitution from dollar funding in swap market to using the central bank swap line for banks with a sufficiently high synthetic dollar cost,* $\ell_{d,t} + \Delta_t + F'(x_{\$,0}^D) > \ell_\$ + \kappa$.

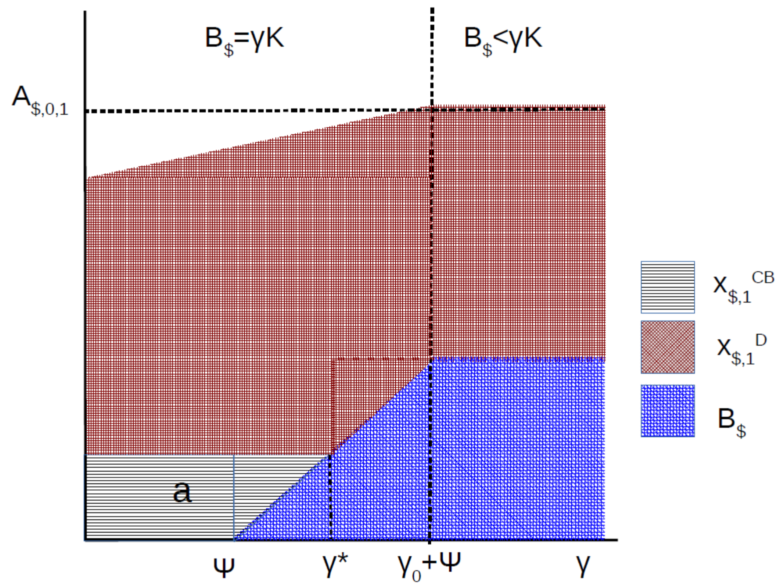
2. *A narrowing of the cross-currency basis in period 2 for banks that are sufficiently constrained with $\gamma < \gamma^*$, where* $\gamma^* = \frac{A_{\$,1} - F'^{-1}(\ell_\$ + \kappa - (\ell_d + \Delta))}{K} - \psi$

$$\frac{\partial \Delta}{\partial x_\$^D} = \begin{cases} 0 & , \gamma \geq \gamma^* \\ \frac{1}{\frac{1}{F''(x_\$^D)} + \frac{N}{\theta\rho\sigma_s^2}} > 0 & , \gamma < \gamma^* \end{cases}.$$

Figure 12 characterizes the bank's equilibrium allocation of dollar funding for different levels of γ. Central bank swap lines are used by a subset of banks that have a higher synthetic dollar funding cost than the rate at which they can obtain dollar funds via the swap line. This subset of banks is for a level of γ less than the threshold γ^*. The substitution from synthetic dollar funding toward the central bank swap lines is denoted by the area a in the diagram. The theoretical effects of swap lines have also been studied in Bahaj and Reis (2018). [33]

[33] They study an exogenous decline in κ to model the effects of a Federal Reserve announcement on October 30, 2011, in which the penalty rate on swap line auctions were reduced from 100 basis points above an interbank dollar rate to 50 basis points. They provide event study analysis showing a decline in CIP deviations following announcement. This model is consistent with their findings, and a decline in κ causes a decline in the ceiling for CIP deviations in equilibrium.

Figure 12: Allocation of direct and synthetic dollar funding sources for a continuum of banks with varying γ. Both initial and final equilibrium after central bank swap line auctions is shown.



C: Model Quantitative Exercise

Calibration

I conduct a simple numerical exercise to test the validity of the model. I estimate the following set of parameters. First, I condense all supply side parameters into a constant Γ, which measures the elasticity of dealer supply to a change in the cross-currency basis.[34] The second parameter I calibrate is α, which constrains the risk-adjusted assets to a fraction of equity. Third, I assume a convex hedging cost $F(x^D_\$) = ax^2$, where a is a scaling factor to be estimated. I estimate these parameters by targeting three moments in the pre-crisis equilibrium. First, I set the pre-crisis CIP deviation to be 5 basis points. This roughly matches deviations prior to 2007, and captures transaction costs in arbitrage. Second, I set the bank's initial allocation of synthetic dollar funding to be 10% of total dollar assets. This is a rough estimate of the ratio of synthetic dollar funding to total dollar assets for Deutsche Bank in 2007.[35] Third, I set a ratio of total dollar assets to equity of one in the initial period.

I normalize the monetary policy parameters r_m and M to a pre-crisis level of $M = 1$ and $r_m = 1\%$. For pass-through of the central bank rate to the deposit and lending rates, I assume simple functional forms, $r_d = r_m + 2\%$, and $c_d = min\{0, r_m\}$. This allows for a domestic interest

[34]Recall the optimal supply of dollars by dealers is $Nx^*_\$ = \frac{N\Delta}{\rho\theta\sigma^2}$. I rewrite optimal dealer supply as $x^*_\$ = \frac{\Delta}{\Gamma}$, where $\Gamma = \frac{\rho\theta\sigma^2}{N}$.

[35]For details of data, please refer to empirical section 4 in which I calculate a proxy for the share of synthetic dollar funding to total dollar assets for U.S. subsidiaries of banks in Eurozone, Japan and Switzerland.

rate margin of 2% when r_m is positive. Another critical parameter is the elasticity of credit spreads to central bank purchases, where I define the domestic credit spread $\ell_d = \bar{\ell}_d - \delta log M_t$. To estimate δ, the effects of the ECB Corporate asset purchase program is estimated to reduce bond yields by approximately 15 basis points. This program represents an approximate 5% increase in the size of the ECB balance sheet, yielding an elasticity of $\delta = 0.03$. I normalize $\gamma = 1$, and in the calibration set this to be the threshold at which the bank transitions from an unconstrained to constrained bank in direct dollar borrowing. Table 7 summarizes all relevant parameters in the calibration.

Table 7: **Calibration of Parameters: Initial equilibrium**

Parameter		
Dealer supply elasticity	Γ	0.0045
Value at Risk	α	4.02
Convex synthetic funding cost $F(x_{\$}^D) = ax^2$	a	0.085
Dollar borrowing constraint	γ	1
Credit spread elasticity to QE ($\ell_d = \bar{\ell}_d - \delta log M_t$)	δ	0.03
Dollar credit spread	$l_{\$}$	3%
Domestic credit spread	$\bar{\ell}_d$	2%
Dollar asset return	$y_{\$}$	4%
domestic asset return	y_d	3%
domestic deposit	c_d	1%

Results

Figure 13 shows the effect of QE and negative interest rates on the equilibrium cross-currency basis. For QE, the pre-crisis CIP deviation of 5 basis points increases to approximately 15 basis points for $M = 2$. The decline in domestic credit spreads induced by QE causes a reallocation toward obtaining dollars via FX swaps.In response to negative interest rates, the bank portfolio rebalances to hold additional dollar assets. As the bank is constrained in direct dollar borrowing, they hedge the additional dollar assets via FX swaps. The effects of negative rates are relatively small compared to QE. This is because, for the given calibration, the convex hedging cost reduces the extent to which dollar assets rise in response to negative rates. A limitation of the preceding results is the linear supply curve of dollars in the FX swap market. In the event dealer supply is fixed due to constraints on dealer leverage, the effects on CIP deviations will be much more acute.

Figure 13: Top: equilibrium Δ and allocation of dollar funding for a range of QE
Bottom: Equilibrium Δ and allocation of dollar funding for a range of central bank rate r_m