Price-setting in the Foreign Exchange Swap Market: Evidence from Order Flow

Olav Syrstad and Ganesh Viswanath-Natraj*

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Abstract

The Foreign Exchange (FX) swap market is the most traded financial market in the world with over 3 Trillion USD daily turnover (BIS Triennial Survey, 2019). Pricing in the FX swap market has been subject to considerable scrutiny since the global financial crisis in 2008, with non-US banks paying significant premiums to swap euros, swiss francs and yen into dollars. Since the financial crisis, dealers set the forward price by learning from order flow. We define order flow as net demand changes that are publicly observable and manifest themselves in FX trading. Using a proprietary dataset on inter-dealer trades, we estimate the price impact of order flow. A 1 standard deviation increase in order flow widens Covered Interest Rate Parity (CIP) deviations for the euro/$, chf/$ and yen/$ by up to 5 basis points. The price impact of order flow is more sensitive to increased dispersion in dollar funding spreads. We then differentiate between shocks to public information, such as quarter-end regulations and monetary announcements, and shocks to private information, such as central bank swap lines. We find evidence of forward prices being set contemporaneously in response to public information. In contrast, forward prices are set based on the arrival of order flow in response to private information.

Keywords: interest rate parity, exchange rates, currency swaps, order flow, dollar funding

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*Norges Bank (Olav.Syrstad@Norges-Bank.no) and Warwick Business School (ganesh.viswanath-natraj@wbs.ac.uk) respectively.We would like to thank Saleem Bahaj, Barry Eichengreen, Gerardo Ferrera, Yuriy Gorodnichenko, Pierre-Olivier Gourinchas, Ingomar Krohn, Richard Lyons, Dagfinn Rime, Andrew Rose, Andreas Schrimpf, Saskia Ter-Ellen and seminar participants at the Australasian Banking and Finance Conference, the Bank of England, the Bank of International Settlements, BI Business School Oslo, Norges Bank and UC Berkeley. The views expressed in this paper are those of the authors and do not necessarily reflect those of Norges Bank.

1 Introduction

Pricing in the Foreign Exchange (FX) swap market has been subject to considerable scrutiny since the global financial crisis, as it no longer obeys the iron law of Covered Interest Rate Parity (CIP). CIP is a constellation of four rates, the spot rate, the forward rate, and the domestic and foreign interest rates. A theory of arbitrage, CIP states that the rate of return on equivalent domestic and foreign assets should equalize after covering exchange rate fluctuations in the FX forward market. Since 2008, CIP deviations have been large and persistent for the euro/$, chf/$ and yen/$ pairs, and have implied a systematic premium for banks to swap euros, swiss francs and yen into dollars through the FX swap market (Figure 1). While much of the literature focuses on why deviations exist, and range from explanations that center on limits to the supply of dollars in the FX swap market due to bank regulations and funding constraints, as well as factors that lead to an excess demand for dollars in the FX swap market, less is understood about the role of price-setting in the FX swap market. In this paper, we examine the role of order flow as a fundamental signal used by dealers to update the price of the forward rate. We define order flow as net demand changes that are publicly observable and only impact price when signals of it are manifested in FX trading.

Prior to the financial crisis, funding spreads in dollars were relatively stable, making price-setting in the FX swap market a straightforward process. The dealer sets the forward rate to match customer orders for swapping euros into dollars with flows from a customer swapping dollars for euros. The post-crisis period is instead characterized by large heterogeneity in funding spreads and leverage constraints. This makes it difficult for dealers to determine the equilibrium price of the forward rate. Therefore, dealers use order flow as a signal to set the forward rate. In this paper, we argue two competing microstructural hypotheses through which price determination is governed by order flow.

The first hypothesis we put forward is the *private information view*, in which dealers reset forward prices based on the arrival of order flow. For example, suppose in response to a shock to its access to dollar funding, a customer now obtains dollars via the FX swap market. The dealer aims to match the customer flows of swapping euros into dollars with flows by other customers of swapping dollars into euros. By matching flows, the dealer aims to reduce the accumulation of inventory. If the dealer cannot meet the customer demands for dollars with matching flows, it submits these excess demands to the inter-dealer market. The net pressure for swapping euros into dollars is observed as order flow in the inter-dealer market. Crucially, these excess demands can then be used by dealers to update the forward rate of the FX swap to balance customer orders. Now, let us consider the alternative hypothesis, in which the information is *public*. For example, consider a scheduled monetary announcement of a central bank. These announcements are publicly announced and the outcomes of the meeting are conveyed to all participants in the financial market. If the announcement is anticipated to raise dollar funding spreads, the dealer can reset the forward rate to equalise funding spreads in different currencies after hedging exchange rate risk. In this setting, dealers adjust the forward rate contemporaneously, and avoid order imbalances.

We formalise the hypotheses in a microstructural model of the FX swap market. The model has three key agents; customers, arbitrageurs and dealers. Customers are swapping domestic currencies, for example euros, swiss francs or yen, into dollars. Arbitrageurs provide flows to match customer demands by borrowing dollars and then lending them in the FX swap market. Dealers act as intermediaries and match the flows of customers and arbitrageurs. Dealers typically try to keep their positions flat to avoid financing inventories Lyons (1995). Dealer aversion to inventory accumulation yields a price-setting condition in which the forward rate is set to correct order imbalances. The model's primary contribution is to map a linear relationship between order flow and price-setting of the forward rate. We can use this framework to study different sources of shocks to customers and dealers. If the shocks are unanticipated by dealers and are based on private information, they are revealed through order flow, which the dealers use to reset the forward rate. Alternatively, if the shock is incorporated in pubic information, dealers reset the forward rate and avoid order imbalances.

We test our microstructural hypotheses of price-setting in the FX swap market using two primary sources. For order flow, we use data from the Thomson Reuters D2000-2 platform used in Rime et al. (2017). This records inter-dealer transactions in 1W FX swaps for the bilateral pairs of euro/\$, yen/\$ and chf/\$. The data includes detailed timestamps of the transaction price, together with bid and ask quotes. Using this information allows us to sign trades. For example, if a dealer posts a market order to swap euros, swiss francs or yen into dollars, we will record that as a buyer initiated transaction. Conversely, if a dealer posts a market order to swap dollars into euros, swiss francs or yen, it is classified as a seller initiated transaction. Signing transactions in this way gives us a measure of order flow, which we define as the net of buyer transactions for swapping euros, swiss francs or yen into dollars at the spot leg of the FX swap. Our second data source is high frequency tick data on 1 week forward and spot rates from Thomson Reuters Tick History to construct a measure of CIP deviations for the 1 Week FX swap.

Our empirical evidence first focuses on deriving estimates for the price impact of order flow. Since the crisis of 2008, a positive 1 standard deviation shock to order flow causes a widening of CIP deviations by up to 5 basis points. We show that the price impact is derived from the change in the forward premium. This is consistent with our model framework, as dealers are updating the forward rate in response to order flow.

To understand why the price impact of order flow is a post crisis phenomenon, we note that since 2008 there is increased dispersion in dollar funding spreads. This makes it difficult for dealers to determine an equilibrium forward price. Therefore we hypothesise that increased dispersion in funding spreads can explain increased price impact since 2008. We measure dispersion in dollar funding spreads using the range of quotes in the Libor fixing in the interbank market. Our results suggest that in days of high funding spreads, which we identify as days with a range of libor quotes exceeding 10 basis points, the price impact of order flow increases by approximately 3 basis points. This is quantitatively significant, and approximately half of the price impact of order flow can be attributed to increased dispersion in funding costs. In additional tests for the robustness of our price impact estimates, we control for quarter-end regulations and scheduled monetary announcements of the European Central Bank (ECB), the Bank of Japan (BOJ) and the Swiss National Bank (SNB). We test for these announcements as there is potential for price-setting to be occurring in response to order flow around these select events, and that is what is driving our result. We find that controlling for these events, the price impact of order flow is largely unchanged.

We now turn to testing the microstructural hypotheses of the whether the public or private information view is relevant in price-determination. First, we test the effect of Federal Reserve Swap lines during the period 2007-2010. In response to rising default risk and a shortage of dollar funding in interbank markets, the Federal Reserve instituted currency swaps with other central banks at a pre-specified exchange rate. These dollar loans were then auctioned off to European, Swiss and Japanese banks in need of dollar funding. Therefore, banks who resorted to the FX swap market during the crisis period, now obtain their dollars via a swap line. [1] To identify the effect of swap lines, we use data on swap allotments, which contain the loan size and terms (typically 1 week) to counterparty central banks during the period. Based on a methodology that controls for feedback effects between CIP deviations, order flow and swap allotments, we find an increase in the flow of Federal Reserve allotments causes a decline in order flow and a narrowing of 1 Week CIP deviations. This is consistent with the private information view, in which dealers reset forward prices through the arrival of order flow. As customer demands for dollars via the FX swap declines, the inter-dealer market observes this through a decline in net transactions to swap euros, swiss francs and yen into dollars. [2]

We then proceed to investigate price determination in the FX swap market around quarter-ends. Agents are incentivized to deleverage in order to meet leverage constraints based on Basel 3 capital requirements. Arbitrageurs supplying dollars in the FX swap market are likely

[1] Alternatively, the swap line also relaxes arbitrageur balance sheet constraints and increases arbitrageurs' ability to supply dollars in the FX swap market. The effects on both customers and dealers will have an equivalent effect of reducing the relative demand for dollar funding in the FX swap market.

[2] We stress that the private information is not the announcement of the swap line itself, which is known to dealers, but the details of counterparties that use the swap line. For example, only a subset of banks that draw on the swap line may have previously been relying on dollar funding via FX swaps. Similarly, banks may now start using these dollar funds to supply dollars in the FX swap market. Both of these outcomes are unanticipated by dealers until they revealed as higher order flow in the FX swap market.

to offload their dollar borrowings and holdings of FX swaps as they deleveraging. All else equal, this causes a decline in the supply of arbitrage capital in the FX swap market. Using high frequency tick data we find that CIP deviations for 1 week FX swaps for the euro/$, yen/$ and chf/$ pairs spike precisely when the FX swap contracts trade over quarter-ends. Taking a microscopic view using high-frequency evidence around quarter-ends, we conclude that there is a contemporaneous adjustment of the forward premium of approximately 30 basis points when the FX swap contract enters the quarter-end period. The contemporaneous adjustment of the forward rate is consistent with the hypothesis of quarter-end regulations being incorporated into dealer information sets. As dealers anticipate deleveraging by agents supplying dollars in the FX swap market, they reset the forward rate to increase the premium of swapping euros, swiss francs or yen into dollars. By adjusting the forward rate contemporaneously, they avoid order imbalances.

Finally, we test for scheduled monetary announcements of the ECB, BOJ and SNB. In response to surprise changes in the risk-free rate, as measured by the overnight index swap (OIS) rate, we find no systematic effect of changes in the risk-free rate on the CIP deviation. Our results are consistent with dealers resetting the forward rate to offset any change in interest rates. As the announcements are publicly known, dealers can reset forward prices contemporaneously, and we find evidence of this using the high frequency response of the forward premium around monetary announcements of the ECB, BOJ and SNB.

We now turn to related literature. The literature on post 2008 CIP violations naturally centre on theories of what are the supply and demand fundamentals in the FX swap market that explain persistent violation of deviations. Theories on limits to the supply of dollars in the FX swap market include rising balance sheet costs and regulatory requirements Du et al. (2018); Liao (2018); Bräuning and Puria (2017), the role of the dollar in constraining leverage Avdjiev et al. (2016), and rising bid-ask spreads due to limited dealer capacity Pinnington and Shamloo (2016), and rising counterparty risk Baba and Packer (2009). Other factors affecting agents demands for dollars in the FX swap market include declines in bank quality, declines in short-term funding, unconventional monetary policies, and central bank swap lines (Rime et al., 2017; Bahaj et al., 2018; Ivashina et al., 2015). This paper contributes to understanding CIP violations by understanding how constraints on changes in customer demand and supply of dollars in the FX swap market can lead to price discovery through order flow. This is a critical component of the FX swap market microstructure and we show empirically that dealers use order flow as a fundamental signal to update the forward price of the FX swap.

The seminal work on market microstructure in FX has typically examined the price impact of order flow on spot foreign exchange markets Evans and Lyons (2002, 2005, 2006); Berger et al. (2008); Rime et al. (2010); Ranaldo and Somogyi (2019). On the empirical front, the FX spot literature finds a significant price impact of order flow, with estimates in Evans and

Lyons (2002) suggesting a $1 Billion USD change in order flow in the USD/Deutschemark market translating to a 50 basis point price move in the spot exchange rate. This literature emphasizes that order flow has an effect on price discovery insofar in that it reflects private information of customers, that are not part of the dealer information set. Microstructure models in Evans and Lyons (2002) have typically used simultaneous trade models in which dealers set prices, and use inter-dealer order flow following a trading round as information to reset prices. In developing our model framework of the FX swap market, we share many of the elements in trading, however we note two clear differences in the FX swap market. The first is that investors in the FX spot market compose of informed and uninformed traders, with informed traders having an information advantage in the price of the spot exchange rate, which is treated as a speculative asset. In contrast, customers in the FX swap market are trading for hedging purposes. Second, we add arbitrageurs to the framework as they attempt to make systematic profits from the mispricing of the forward rate. We derive a price-setting relation in which the CIP deviation is linearly related to order flow. This is similar to microstructure models of the exchange rate, in which exchange rate returns are linearly related to order flow.

Finally, we relate to a recent interest in understanding the impact of order flow in FX swaps. This has been a post-crisis phenomenon, as prior to 2008 covered interest rate parity violations were small and the forward rate was set mechanically in accordance with the covered interest rate parity condition. However, since 2008, there is increasing evidence on heterogeneous funding spreads, and the role of leverage playing a role in the ability to absorb order imbalances. Evidence in Cenedese et al. (2019) and Rime et al. (2017) find evidence that order flow, measured as the net of trades swapping domestic currency (euros, yen and swiss francs) to dollars, is positively associated with a widening of cross-currency basis for these currency pairs. We extend their work in several ways. Through a model framework, we derive the price impact of order flow on the FX swap market through an inter-dealer market that sets forward prices to minimise inventory accumulation. Second, we test the hypotheses through which order flow has price impact using swap repository data for the 1 Week FX swap. We find that the source of information matters: in response to public announcements, dealers set the forward price contemporaneously. In contrast, order flow plays a significant role in price-setting of the forward rate in response to private information, and this is substantiated through the allotment of central bank swap lines by the Federal Reserve in the period 2008-2010.

The paper is outlined as follows. In section 2, we outline definitions of covered interest rate parity, FX swaps and order flow. In section 3, we develop a model of the microstructure of the FX swap market, and derive a price-setting rule that relates the forward rate of the swap to order flow observed in the inter-dealer market. In section 4, we outline our measurement of covered interest rate parity violations and datasets on order flow. In section 5, we first provide baseline estimates of the price impact of order flow. In section 6, we empirically test the microstructure hypotheses of how prices are determined in response to public and private sources of information, using the response of the FX swap market in response to quarter-end bank regulations and central bank swap lines. In section 7 we conclude.

2 Definitions

Covered Interest Rate Parity

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. We document this in Figure 1, which plots 1 year CIP deviations for the euro/\$, chf/\$ and yen/\$ pairs.

In this paper, we study price-setting of the FX swap. In our context, this specifically refers to a dealer setting the forward rate of the swap. In pre-crisis times, setting the forward rate was a rather mechanical exercise, the dealer sets the forward rate so that the returns in dollars and euros are equalized when accounting for exchange rate risk using the forward contract. We make this distinction in equation 2, where in the pre-crisis period, deviations were rather small, $\Delta_{pre-crisis} \approx 0$, and so the forward rate is set by dealers consistent with covered interest rate parity arbitrage taking place.

$$\Delta_{pre-crisis} \approx 0 \implies F = S\frac{1 + r^f_\$}{1 + r^f_d} \tag{2}$$

In the post-crisis period, significant deviations from parity suggest dealers set the forward rate in response to underlying demand and supply fundamentals in the FX swap market. Price determination is complicated by the fact that there also exist substantial heterogeneity in funding spreads, leverage constraints and customer quality during this period. As we will illustrate in our model, dealers update the forward rate of the swap in response to demand and supply fundamentals in the FX swap market.

Foreign exchange and cross-currency 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. [3] We illustrate the legs of the FX swap in Figure 2. 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 3. 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, which is connected to the forward rate by equation 2.

Order Flow and the Inter-Dealer market

Based on our preceding discussion of FX swaps, we can classify transactions based on whether they are "buyer" or "seller" initiated. Buyer initiated transactions are classified as

[3] 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 dollar receivables with euros.

customers executing a market order to swap Euros, Swiss Francs or Yen into dollars at the spot leg of the FX swap contract. Conversely, seller initiated transactions execute a market order to swap dollars into Euros, Swiss Francs or Yen. We will use this sign convention in our empirical evidence. Order Flow in the FX swap market is then measured as net buyer initiated transactions for swapping euros, swiss francs and yen into dollars. This is the fundamental signal used by dealers to update the price of the FX swap.

Dealers in our framework are intermediaries that are matching opposing flows in the FX swap market. A dealer aims to match customer orders for swapping euros currency into dollars with flows from a customer swapping dollars for euros (Figure 4, left). In contrast, suppose dealers inhibit their ability to match customer flows. In the event of unmatched customer flows, the dealer submits excess demands for swapping euros into dollars to the inter-dealer market (Figure 4, right). The net pressure for swapping euros into dollars is observed as order flow in the inter-dealer market. Critically, we assume that dealers face inventory risk, this is in accordance with empirical evidence that dealers aim to set prices to match flows and avoid inventory accumulation Lyons (1995).

3 Model

We first introduce the three types of agents in the model, customers, arbitrageurs, and dealers. Customers include banks, other financial institutions and non-financial institutions that manage currency mismatch between assets and liabilities by hedging their positions via FX swaps. They submit their orders to dealers, who match customer interests themselves or turn to the inter-dealer market to match the trade. Additionally to customers, there are a distinct group of arbitrageurs. The arbitrageurs can step in and supply dollars in the FX swap market to earn arbitrage profits from mispricing of the forward rate in response to underlying demand for dollars from customer flows. The third group of agents are dealers, who set the forward price of the FX swap. The objective of dealers are to match customer flows of swapping euros into dollars with opposing flows of swapping dollars into euros by the set of arbitrageurs. Any unmatched flows are submitted to the inter-dealer market and are observed as order flow. The key assumption in price-setting is that the inter-dealer market sets the forward rate to avoid order imbalances. This is consistent with market microstructure theories of dealers keeping positions flat and avoiding inventory accumulation (Lyons, 1995).

The primary contribution of the model is in deriving a relationship between order flow and price-setting of the forward rate. Additional testable implications include an analysis of the source of shocks to order flow. Shocks to customer order flow can come from unanticipated changes in customer quality and access to dollar funding markets. Shocks to arbitrageur capital take the form of heterogeneous dollar funding spreads and leverage constraints.

Arbitrageurs

Following Sushko et al. (2017), we model an arbitrageur that has expected exponential utility over next period wealth W_{t+1}. Formally, we define $U_t = \mathbb{E}_t\left[-e^{-\rho W_{t+}}\right]$, where ρ is a measure of risk aversion. The arbitrageur decides to lend x_t dollars in the FX swap market. To do so, they first borrow at the dollar risk-free rate $r^f_\$$. The dealer 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 the forward rate f_t. During the contract, they invest the domestic currency, at a risk-free rate r^f_d. The net profit they make per unit of arbitrage is defined as the cross-currency basis, Δ_t,which is the excess of the forward premium over the interest rate differential, $\Delta_t = f_t - s_t - (r^f_\$ - r^f_d)$.[4]

While the above analysis holds for the pre-crisis period of 2008, in the post-period there has been increased funding spreads in dollars relative to funding spreads in other currencies. For example, suppose that to raise dollar funding, the cost of dollars is the risk-free rate with the addition of a funding cost $c_{\$,j,t}$. Similarly, the return on domestic currency is the risk-free rate plus the addition of a funding cost $c_{d,j,t}$. Therefore, the difference in dollar and domestic funding cost $c_{\$,j,t} - c_{d,j,t}$, which we call a funding spread, is an additional cost of arbitrage.

The arbitrageur bears exchange rate risk. In the event of a default with a given probability θ, the dealer 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}. We can write the evolution of wealth in the next period 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. We capture costs to arbitrageur leverage, $\phi_t\left(\frac{x}{W}\right)$, with $\phi_t\left(.\right) > 0$. This is a stylized way of capturing regulatory factors such as requirements on a minimum level of risk-weighted capital to assets, and other costs of scaling the balance sheet to conduct CIP arbitrage.

$$W_{t+1} = \underbrace{W_t(1+r^f_\$)}_{\text{return on wealth}} + \underbrace{x_{\$,t}\Delta_t}_{\text{cip arbitrage}} - \underbrace{x_{\$,t}(c_{\$,j,t} - c_{d,j,t})}_{\text{funding spreads}} + \underbrace{\theta x_t(s_{t+1} - f_t)}_{\text{counterparty risk}} - \underbrace{W_t\phi_t\left(\frac{x_t}{W_t}\right)}_{\text{leverage constraint}} \tag{3}$$

Assuming $s_{t+1} \sim N(f_t, \sigma_s^2)$, and drawing on the properties of the exponential distribution, maximizing the log of expected utility is equivalent to mean-variance preferences over wealth.

$$\max_{x^*_{\$,t}} \rho\left(W_t(1+r^f_\$) + x_{\$,t}\Delta_t - x_{\$,t}(c_{\$,j,t} - c_{d,j,t}) - \frac{1}{2}\rho\theta^2 x^2_{\$,t}\sigma^2 - W_t\phi_t\left(\frac{x_t}{W_t}\right)\right) \tag{4}$$

[4] Note that the definition of the cross-currency basis in the model is the negative of the cross-currency basis expressed in the empirical evidence. We change the notation for the model as we are taking the perspective of an arbitrageur supplying dollars in the FX swap market.

The optimal supply of dollars by an arbitrageur is given by x_t^*. Dealer supply of dollars is positively associated with the forward premium (and hence cross-currency basis).

$$x^*_{\$,t} = \frac{\Delta_t - (c_{\$,j,t} - c_{d,j,t}) - \phi'_j\left(\frac{x_t}{W_t}\right)}{\rho\theta^2\sigma^2} \tag{5}$$

In addition, we model two additional costs on the arbitrageur's balance sheet that limit the extent of arbitrage undertaken. The first is differences in dollar funding spreads, which increases the effective cost of borrowing in dollars to execute the CIP arbitrage trade. The funding spread heterogeneity is a post-crisis feature and is typically represented as higher credit spreads in dollars, as well as more dispersion in Libor rates for banks (Rime et al., 2017). Second is the leverage constraint. As the ratio of debt to total assets increases with more arbitrage capital, so does the marginal cost of obtaining dollars. For example, in Bräuning and Puria (2017) they find evidence that the size of the swap position leads to higher forward premiums charged by dealers, all else equal. This is especially heightened in quarter-end periods when leverage constraints prevent agents from borrowing for arbitrage capital (Du et al., 2018; Cenedese et al., 2019). Both funding spreads and leverage are idiosyncratic, that is, heterogeneity in arbitrageur funding spreads and leverage can make it more difficult for the inter-dealer market to predict order imbalances. We elaborate on this heterogeneity further in a following section where we set out the price-setting condition in the inter-dealer market.

Customers

Customers, typically banks, use the FX swap market to swap domestic currency (euros, swiss francs and yen) into dollars to hedge their dollar asset positions. We capture customer demands by the following stylized function, where banks are in a continuum [0,1] indexed by bank quality θ_b and the cross-currency basis Δ. Importantly, $x^D_{\$,t}$ is a measure of the net demand for dollars at the spot leg of the FX swap.

$$x^D_{\$,t} = \int_0^1 f(\theta_b, \Delta, A_\$ - L_\$)db \tag{6}$$

The first determinant of net demand for dollars in the FX swap market is θ_b, which measures bank quality. All else equal, banks with higher quality are more likely to obtain dollars directly via commercial paper markets or bank deposits. Therefore demands for dollar funding via FX swaps is inversely related to bank quality. The decline in bank quality and the corresponding increase in counterparty risk are key determinants of the increased demand for dollar constrained banks in the FX swap market in 2008 (Baba and Packer, 2009). The second determinant of net demand is the cross-currency basis Δ. All else equal, a higher cross-currency basis implies a synthetic dollar borrowing premium. This increases the net cost of swapping euros, swiss francs and yen into dollars, all else equal. Evidence in Eguren Martin et al. (2018) suggests that in response to shocks to the basis, banks' net demand for dollars in the FX swap market declines. Our last determinant is customer hedging demands, which is determined by the difference in dollar assets and dollar liabilities. More concretely, if the difference between assets and liabilities denominated in dollars is positive, $A_{\$} - L_{\$} > 0$, the bank hedges the currency exposure by dollar funding via a FX swap. This is consistent with evidence that countries with a larger dollar funding gap, like Japan, are associated with wider CIP deviations (Sushko et al., 2017).

Inter-Dealer Market

We have defined customers and arbitrageurs. Each of these agents are price-takers, and go to a market-maker to find a counter-party to take the other side of the trade. The market-maker is the dealer in our model. The dealer's objective is to match flows of swapping domestic currency (for example euros, swiss francs, yen) into dollars with opposing flows. This is consistent with theories of market micro structure where dealers are sufficiently risk averse to holding inventory (for eg. see Lyons (1995). We denote the net dollar demands by customers to dealer j by $x^D_{\$,j}$. Denote the net supply of dollars by arbitrageurs to dealer j by $x^*_{\$,t,j}$. Unmatched flows in dollars are submitted to the inter-dealer market. We illustrate the unmatched flows of a dealer in Figure 5. The dealer submits the excess demand for dollar funding to the inter-dealer market, and this is observed as $OF_{t,j}$ in the Figure. Aggregating across all dealers, we obtain an expression for inter-dealer order flow OF_t, in equation 7. Inter-dealer order flow is equal to the net buying pressure of swapping euros, swiss francs or yen (domestic currency) into dollars. 'Net customer demands for dollars at the spot leg of the FX swap is equal to $x^D_{\$,t}$. Net supply of dollars by N symmetric arbitrageurs in the FX swap market is given by $\sum_{i=1}^{N} x^*_{\$,t}$.

$$OF_t = x^D_{\$,t} - \sum_{i=1}^{N} x^*_{\$,t} \tag{7}$$

To illustrate the timing of customer-dealer trades and price-setting, Figure 6 depicts a two period model, in which customers and dealers trade at the beginning of each period. Immediately after each period of trading, the inter-dealer market observes order flow. Dealers then set the forward rate of the FX swap, and hence the cross-currency basis Δ, to set expected order imbalances to zero for the next period of trading.

Definition [Price setting]: *The inter-dealer market sets a forward price to set inter-dealer order flow to be zero, based on an information set that includes information on current and past prices, and customer and arbitrageur fundamentals.*

$$\mathbb{E}_t \left[OF_t(\Delta_t)|\mathcal{I}_t\right] = 0 \tag{8}$$

The price-setting condition is implicitly assuming an inter-dealer market that sets a common price for all dealers. This is a simplifying assumption, as if dealers set different prices, this would not be a sustainable equilibrium as customers will only execute swap trades with the dealer that sets the most favorable forward price. Combining equations 7 and 8, we can rewrite the order flow in period t as the unanticipated components of customer demand and dealer supply of dollars in the FX swap market.

$$OF_t = x^D_{\$,t} - \mathbb{E}\left[x^D_{\$,t}|\mathcal{I}_t\right] - \sum_{j=1}^{N}\left(x^*_{j,t} - \mathbb{E}\left[x^*_{j,t}|\mathcal{I}_t\right]\right) \tag{9}$$

In the model, order flow responds to changes to demand fundamentals that are not forecast by dealers. This provides a simple decomposition of order imbalances into unexpected idiosyncratic shocks to customers and dealers, shown in equation 10. The first term reflects unanticipated shocks to customer type and funding spreads. For example, the inter-dealer market may not directly observe customer types, such as credit ratings and their ability to borrow dollars in alternative markets. The second term reflects unanticipated changes in funding spreads. The third term reflects rises in the cost of leverage.

$$OF_t = \underbrace{\int_0^1 f(\theta_b, .) - \mathbb{E}\left[f(\theta_b, .)|\mathcal{I}_t\right] db}_{\text{customer type and funding spreads}} + \frac{1}{\rho\theta^2\sigma^2}\sum_{j=1}^{N}\Bigg(\underbrace{c_{\$,j,t} - c_{\$,d,t} - \mathbb{E}\left[c_{\$,j,t} - c_{\$,d,t}|\mathcal{I}_t\right]}_{\text{funding spreads}} + \underbrace{\phi'_{j,t}\left(\frac{x}{W}\right) - \mathbb{E}\left[\phi'_{j,t}\left(\frac{x}{W}\right)|\mathcal{I}_t\right]}_{\text{leverage constraints}} \tag{10}$$

Finally, we can solve for the equilibrium cross-currency basis Δ, can be derived from setting expected order flow to zero, in equation 11. Intuitively, an increase in customer demands, an increase in dollar funding spreads relative to domestic funding spreads, or a tightening of leverage constraints on dealers, leads to a widening of the basis.

$$\Delta_t = \mathbb{E}\left[c_{\$,j,t} - c_{d,j,t}|\mathcal{I}_t\right] + \mathbb{E}\left[\phi'_{j,t}\left(\frac{x}{W}\right)|\mathcal{I}_t\right] + \frac{\rho\theta^2\sigma^2}{N}\int_0^1 \mathbb{E}\left[f(\theta_b, .)|\mathcal{I}_t\right] \tag{11}$$

We can use the framework to study the price impact of order flow, as well as the propagation of shocks to customer demands and dealer supply on price-setting in the FX swap market.

Proposition 1: price impact of order flow

A positive shock to order flow in period t implies a widening of CIP deviations, with the price sensitivity $\beta = \frac{\rho\theta^2\sigma^2}{N}$.

$$\Delta_{t+1} - \Delta_t = \beta OF_t \tag{12}$$

The price impact of order flow is seen in equation 13 is governed by β, which is related positively to variance of the exchange rate, counterparty risk, and negatively related to the number of arbitrageurs N. This contrasts to the β in microstructure models of the spot FX market, which typically measures the relative share of informed traders (Evans and Lyons, 2002). We differentiate our price impact equation in that FX swaps do not feature uninformed traders, and rely on customers that use FX swaps for largely hedging purposes. One important implication is an efficient market with no limits to arbitrage, $N \to \infty$ and there is a zero impact of order flow. In this case, a dealer will always have matched flows, as there is an elastic supply of arbitrage capital to take the other side of customer trades. We can use this framework to analyse sources of information shocks to customers and dealers, which we outline in propositions 2 and 3.

Proposition 2: price impact of customer order flow

A positive shock to bank quality θ_b causes a decline in bank demands for dollar funding in FX swap market, a decrease in order flow in period t and a narrowing of CIP deviations in period $t+1$.

$$\Delta_{t+1} - \Delta_t = \beta \underbrace{\int_0^1 f(\theta_b, .) - \mathbb{E}\left[f(\theta_b, .)|\mathcal{I}_t\right] db}_{\text{customer type and funding spreads}} \tag{13}$$

An example of a shock to bank quality that we test empirically is the introduction of central bank swap lines, which provides an alternative source of dollar funding for banks facing a dollar shortage (Bahaj et al., 2018). Central bank swap lines by the Federal Reserve provide incremental dollar liquidity to sufficiently dollar constrained banks. As banks of low quality are more likely to use central bank swap lines as a way to meet dollar funding, we can interpret this as reducing customer demand for dollars via FX swaps. Crucially, if the swap line auctions to dollar constrained banks are private information, this results in a decline in order flow, causing a decline in the forward premium of the swap trade.

Proposition 3: price impact of arbitrage capital

A positive shock to dollar funding spreads or leverage constraints causes a decline in supply of dollar funding in FX swap market, a rise in order flow in period t and a widening of CIP deviations in period $t+1$.

$$\Delta_{t+1} - \Delta_t = \frac{1}{N}\sum_{j=1}^{N}\left(\underbrace{c_{\$,j,t} - c_{d,j,t} - \mathbb{E}\left[c_{\$,j,t} - c_{d,j,t}|\mathcal{I}_t\right]}_{\text{funding spreads}} + \underbrace{\phi'_{j,t}\left(\frac{x}{W}\right) - \mathbb{E}\left[\phi'_{j,t}\left(\frac{x}{W}\right)|\mathcal{I}_t\right]}_{\text{leverage constraints}}\right) \quad (14)$$

Proposition 3 shows that a reduction in arbitrage capital due to an unanticipated rise in funding spreads and leverage constraints increases order flow and has subsequent price impact in the FX swap market. Limits to arbitrage capital are particularly pronounced during quarter-end regulations, and there is micro level evidence suggesting dealers that are more leveraged are more sensitive to order imbalances and demand a higher forward premium on the contract (Du et al., 2018; Cenedese et al., 2019). Another feature of proposition 3 states that an increase in heterogeneity of funding spreads or leverage constraints can also lead to price impact, a feature that is consistent with the empirical findings of Rime et al. (2017). If there is an increased dispersion of funding spreads, dealers will use order flow as a signal to update the price of the FX swap. To conclude, the model has provided a framework to show how unanticipated shocks to customer demand, funding spreads and leverage constraints can translate to an increase in inter-dealer order flow. This causes dealers need to reset the forward premium of the FX swap to offset order flow, resulting in a widening of the cross-currency basis. This is consistent with microstructure theories on inventory control; dealers are sufficiently averse to holding inventory and update the forward rate as a response to avoid inventory accumulation. We test three predictions in our empirical evidence. First, we test equation 13 directly to measure the price impact of order imbalances. We then test for order flow and price effects following quarter-end regulations, and central bank swap lines.

4 Data

4.1 Covered Interest Rate Parity

To compute deviations at the 1 week maturity, we use Thomson Reuters tick history which contains historical data on spot and 1 week forward prices of the euro/\$, chf/\$ and yen/\$ pairs. Swap points, also referred to as pips, are used to get the forward exchange rate, $F = S + \frac{sp}{10^4}$, where we express S and F as dollars per unit of domestic currency, and so the dollar is classified as the quoting currency. The CIP deviation we calculate in equation 15 is expressed as the difference between the local dollar borrowing rate less the synthetic dollar borrowing rate, where i_q is the US interest rate, i_b is the base interest rate (denominated in euros, swiss francs or yen), S_a is the spot rate at ask and F_b is the bid forward rate. A negative Δ indicates that synthetic dollar borrowing costs exceed local borrowing costs, and this is indeed the case for the euro/\$, yen/\$ and chf/\$ pairs. For a measure of risk-free rates, we use the 1 week Libor in the quoting and base currencies. In constructing the CIP deviation, we convert our forward premium $\frac{F}{S}$ to annualised percentage points in order to construct a measure of 1 week CIP deviations in annualised terms.

$$CIP_t = 1 + i_{q,t} - \frac{F_{b,t}}{S_{a,t}}(1 + i_{b,t}) \tag{15}$$

Summary statistics for the three pairs are provided in Table 1, for the euro/\$, chf/\$ and yen/\$ pairs respectively. CIP deviations are much wider in the post 2008 period, with an average of 30 basis points for all pairs. Average deviations are negative, suggesting that on average, the US dollar libor rate is less than a synthetic libor rate based on borrowing in euros, swiss francs or yen and swapping into dollars using a forward contract. The range of CIP deviations also increases significantly with measured spikes of up to -300 basis points. These spikes correspond to quarter-end periods, which we investigate empirically in following sections.

4.2 Order Flow

Order flow is defined as the net of buyer initiated transactions. We define a transaction as buyer initiated if it is initiated by a counterparty swapping euros, Swiss francs and yen into dollars. Conversely, a transaction is seller initiated if the transaction is swapping dollars into euros, swiss francs and yen. To measure order flow at short-term maturities, we use the Reuters D2000-2 trading platform available at Norges bank, which contains inter-dealer trades from 2005 to 2017 in FX swaps for the euro/\$, chf/\$ and yen/\$ pairs. We use the 1 Week maturity as it is the most liquid and traded pair at maturities less than 1 month. This dataset is also used to construct order flow for FX swaps in Rime et al. (2017). The dataset has quotes in the inter-dealer market, with columns indicating bid price, ask price, a timestamp of the quote to the nearest second, and a column for the market price when a trade has occurred. Using this data, we can match transaction prices to the bid and ask price quotes at the timestamp of the trade. We follow the algorithm provided in Lee and Ready (1991), which is commonly used to sign transactions as buyer or seller initiated based on bid and ask quotes.

Formally, let us define p_T is the transaction price, p_a is the ask price and p_b is the bid price. The algorithm is designed to sign the transaction as buyer (seller) initiated if the transaction price is closer to the ask (bid). We illustrate more formally the algorithm below. [5]

1. If $p_{T,t} < \frac{p_{a,t}+p_{b,t}}{2}$, transaction is seller initiated
2. If $p_{T,t} > \frac{p_{a,t}+p_{b,t}}{2}$, transaction is buyer initiated

The measure of order flow is then given as the net of buyer initiated transactions, where buyer initiated transactions are signed +1 and seller initiated transactions are signed -1.

$$OF_t^{count} = \sum_{k=t_0}^{k=t} \mathbb{1}[T_k = B] - \mathbb{1}[T_k = S]$$

Summary statistics of order flow using the inter-dealer trades are provided in Table 2. The mean of net buyer initiated trades is close to zero, and the standard deviation of trades ranges from 2-5 net buyer transactions per day. The euro/$ pair has the highest range of order flow, with a range of [-30,+30]. We provide plots of daily order flow, cumulative order flow and the 1 Week CIP deviation in Figure 2.

In addition to data on FX swaps, we also use data on cross-currency swaps at longer maturities of greater than 3 months. This data is obtained from a swap repository facility available at Bloomberg SDR Terminal, recording a set of customer-dealer transactions in cross-currency swaps for financial institutions that are compliant with the CFTC. This captures a subset of the market insofar as they are institutions that report to the Bloomberg SDR facility, and is available since 2013. We report summary statistics and plots of order flow for the 1 Year Cross-Currency Swap in the Appendix A. We treat our data on cross-currency swaps as a secondary source in our empirical evidence because we have customer-dealer trades instead of inter-dealer trades for the 1 Week FX swaps.[6]

5 Price Impact of Order Flow

Baseline specification

In this section we take the testable implications of the model framework to the data. First, we examine the price impact of order flow based on the price-setting equation outlined in the model. Based on our model, we concluded that a rise in order flow is consistent with excess demands for swapping domestic currency into dollars. As dealers are averse to holding inventory, the inter-dealer market resets the forward rate to offset order flow. This leads to an increase in

[5] In the event that the transaction price is at the mid point, the past history of bid and ask prices are used to infer the sign of the trade. Alternatively, if there is no past history of bid and ask prices, the trade cannot be signed.

[6] Issues of sample selection can be a problem. If the swap repository includes a subset of customer-dealer trades, results are subject to idiosyncratic liquidity needs of customers, and order flow measures constructed from this data are less likely to correlate with a measure of inter-dealer order flow.

the forward premium and a widening of deviations of covered interest rate parity. Our baseline specification in equation 19 is measuring the price impact of order flow. On the left hand side, we measure the daily change in covered interest-rate parity violations using end of day prices. The order flow for 1 week FX swaps are measured in counts as we do not have trade volume in the TR D2000-2 database. We run the specification for the euro/\$, chf/\$ and yen/\$ pairs separately, and divide our sample into two periods, the pre-2008 period (which runs from 2005 to end of 2007), and the post 2008 period (which runs to the end of the sample in 2017).

$$CIP_t - CIP_{t-1} = \alpha + \beta OF_t + \epsilon_t \tag{16}$$

Our results for the 1 week euro/\$, chf/\$ and yen/\$ bilateral pairs are estimated in Table 3. We find that order flow has significant price impact in the post 2008 period for all 3 pairs, with a 1 standard deviation change in order flow widening covered interest rate parity violations by approximately 5 basis points. In contrast, there is no significance in the pre 2008 period. The insignificant price impact of order flow in the pre 2008 period is intuitive as covered interest rate parity held tightly during this period, with average violations bounded within transaction costs.

Effects on Forward Premium

Our theory of price-setting in the FX swap market states that dealers update the forward rate of the swap in response to order flow. Decomposing the 1 week cip deviation into a forward premium component and an interest rate differential, we expect that all of the price impact of order flow is observed only in the forward premium. Restricting the sample to the post 2008 period, the regression results for the forward premium and interest rate differential are presented in Table 4. In columns 1, 3 and 5, we find that the reaction of the forward premium to the order flow explains the entire reaction of the change in the covered interest rate parity violation, whereas in columns 2, 4 and 6, we find a weak statistical effect on the interest rates.

This means the forward rate is set mechanically to make the covered interest rate parity hold. Second, in the post 2008 period, there is increased variability in funding spreads and leverage constraints, complicating price determination in the FX swap market. Therefore dealers in the post 2008 period are using the order flow as a public signal to update the forward rate of the swap.

Dynamic effects

In addition to measuring the contemporaneous price impact of order flow, we test for dynamic effects using a structural vector autoregression (VAR) framework. We use this method as equation 19, while capturing the contemporaneous price impact, does not examine effects on covered interest rate parity violations at longer horizons. Following the work of Hasbrouck (1991); Ranaldo and Somogyi (2019), we estimate the following bivariate VAR, illustrated in equations 17 and 18.

$$CIP_t = \alpha_1 + \sum_{k=1}^{L} \gamma_{1,k} CIP_{t-k} + \sum_{k=0}^{L} \beta_{1,k} OF_{t-k} + \epsilon_{1,t} \tag{17}$$

$$OF_t = \alpha_2 + \sum_{k=1}^{L} \gamma_{2,k} CIP_{t-k} + \sum_{k=1}^{L} \beta_{2,k} OF_{t-k} + \epsilon_{2,t} \tag{18}$$

In our baseline specification, we use $L = 7$ lags. we assume that shocks to order flow are impounded in the price contemporaneously, however shocks to price affect order flow with a lag. The identification assumption is consistent with causality running from order flow to price-setting of the FX swap. Therefore in equation 17, a contemporaneous shock to daily order flow is impounded in the closing price, which is consistent with the price-setting equation derived in our model framework. Conversely, we only allow for shocks to prices to affect order flow with a lag. Based on our specification, we test the effects of a 1 standard deviation shock to order flow on the CIP deviations for the euro/\$, chf/\$ and yen/\$ pairs in Figure 8. On the left panel, we test for effects during the pre 2008 period, and observe no systematic effect of order flow on the cross-currency basis for all 3 pairs. In the post 2008 period, we find the cross-currency basis widens by approximately 3-5 basis points contemporaneously. However the price impact of order flow decays to zero for all pairs after approximately 3-5 days following the shock to the order flow. this is intuitive as a shock to order flow is impounded in the price contemporaneously, and it contains less relevant information over a longer horizon. Crucially, the contemporaenous price impact of order flow is consistent with estimates in Table 3. For dynamic effects of order flow shocks for cross-currency swaps (swaps at longer horizons ranging from 1Y to 10Y), we refer the reader to Appendix B.

5.1 Robustness tests

Price Impact around high dispersion in funding costs

This means the forward rate is set mechanically to make the covered interest rate parity hold. Second, in the post 2008 period, there is increased variability in funding spreads and leverage constraints, complicating price determination in the FX swap market. Therefore dealers in the post 2008 period are using the order flow as a public signal to update the forward rate of the swap.

In the model, order flow arises as unanticipated changes in customer demand, due to changes in bank quality, or unanticipated changes in arbitrage capital from leverage constraints or funding spreads. We use the daily quotes by banks to construct a proxy for funding spreads in dollars, as the difference between the daily maximum and minimum Libor quote. The Libor fixing is set at approximately 12 noon in London each day, and the range of quotes on a given day provides us an approximate measure of the spread in funding spreads facing agents supplying dollars in the FX swap market. Therefore, to test this formally, we divide our sample into days where the range of minimum and maximum libor quotes is less or greater than 10 basis points.[7]

Table 5 presents results of the price impact of order flow. Consistent with our theory, we find that the price impact of order flow is significantly higher during periods of high dispersion in Libor quotes, with the price impact increasing. The results are suggestive that as there is more heterogeneity in funding spreads, order flow conveys more information to dealers in updating the forward price of the FX swap.

Price impact around quarter-ends

We test for the impact of quarter-end regulations on the pricing of short-term FX swaps. At quarter-ends, there is an incentive for financial institutions to window-dress balance sheets in order to meet leverage requirements imposed by Basel 3.[8] To test the effects of quarter-end regulations, we augment our price-setting equation with variables that account for the quarter-end period. Our variable of interest is $Qend \times post2015 \times OF$, which captures any additional price-impact of order flow during the quarter-end period. Results of the specification are provided in Table 6. We find, firstly, that the unconditional price-impact of order flow coefficient β is unchanged from before. This shows that the price impact of order flow is robust to the jumps evident during the quarter-end period.

$$CIP_t - CIP_{t-1} = \alpha + \beta_1 OF_t + \beta_2 Post2015 + \beta_3 Qend_t + \beta_4 Qend \times OF_t + \beta_5 Qend \times post2015 \times OF_t + \epsilon_t \tag{19}$$

Price impact: monetary announcements

A final robustness test is examining whether the price impact of order flow is impacted differently during scheduled monetary announcements. We augment our specification in equation 20, with $\mathbb{1}[MP_t]$ a dummy variable for scheduled announcements of the ECB for the euro/\$, BOJ for the yen/\$ and SNB for the chf/\$ CIP deviation respectively. In Table 7, we test for the price impact of order flow. With respect to each currency pair, we find the price impact of order flow after accounting for monetary announcements are similar, with etimates between 3

[7]We choose this as the threshold as it is the median range of libor quotes during this period

[8]Basel 3 requires a minimum risk-adjusted capital to assets ratio.

and 4 basis points.

$$CIP_t - CIP_{t-1} = \alpha + \gamma \mathbb{1}[MP_t] + \beta OF_t + \delta OF_t \times \mathbb{1}[MP_t] + \epsilon_t \tag{20}$$

6 Microstructure Tests: Public vs Private Information Shocks

In this section we test our microstructural hypotheses of how price-setting is determined in the FX swap market. Our two hypotheses reflect the differences in price-setting based on whether the shock to customer demands or arbitrage capital is based on private or public information. To illustrate the two hypotheses, we document the response of order flow and the CIP deviation to a shock to customer flows In Figure 9. Under the hypothesis of public information, dealers reset the forward rate contemporaneously. In contrast, if the shock is private information, dealers set the price of the forward in response to order flow. In this section, with reference to examples, we examine how price-setting in the FX swap market is determined in response to central bank swap lines and quarter-end reporting requirements. We find evidence that central bank swap lines constitutes private information: swap line allotments cause price-setting through the arrival of order flow. In contrast, as quarter-end reporting obligations constitute public information, we observe contemporaneous adjustment of the forward rate.

6.1 Central Bank Swap Lines

Central bank swap lines provide incremental dollar liquidity to sufficiently dollar constrained banks. Banks who resorted to the FX swap market for dollars in the crisis period now obtained their dollars via a central bank swap line. The effect of these policies are to reduce the demand for dollar funding in the FX swap market. Price effects, in reducing CIP deviations, have been well documented, with the rate at which the Federal Reserve lends to counterparty central banks enforcing a ceiling on CIP deviations (Bahaj et al., 2018). We use the central bank swap lines to test the following microstructure hypotheses of how price-setting is determined in the FX swap market. If swap lines are public information, price effects are contemporaneous. In contrast, if swap lines constitutes private information, price effects are due to the arrival of order flow.

We now illustrate the hypothesis that the swap lines constitutes private information. The Federal Reserve extends a swap line to the ECB. The ECB then auctions those dollars to Eurozone banks. While the size of allotments are made publicly available, the details of which banks have access to the swap line are unknown to the dealers in the FX swap market. Therefore, under the hypothesis that the information is private, dealers can only update forward prices once they observe order flow. Swap lines can either be extended to customers swapping euros into dollars, or arbitrageurs supplying dollars in the FX swap market. The effect of swap lines on customer demands is therefore revealed through a decline in buyer initiated transactions for dollars in the euro/$ FX swap market. Alternatively, if the central bank swap lines are instead allocated to arbitrageurs supplying dollars in the swap market, we expect an increase in seller initiated transactions for dollars in the euro/$ FX swap market. In either case, we predict an increase in allotments to reduce order flow, which we document schematically in Figure **??**.

To test this, we use data on Federal Reserve swap line allotments to counterparty banks during the period of 2008-2010. The data contains a record of every transaction made, with both amounts and maturity listed. The maturity of a swap line can range from one week to 1 month. At a daily frequency, we compute the total stock of allottments as the total amount of all loans made by the Federal Reserve to counterparty central banks, less any loans that have matured. The daily change in stocks provides us a flow measure of allotments. This is the most direct measure of incremental liquidity provided by the Federal Reserve to foreign (non U.S.) banks. We construct a measure of total allotments for the central bank swap line. Figure 10 plots the total allotments outstanding to the ECB, BOJ and SNB, as well as loans made to banks in the Eurozone, Japan and Switzerland. At the height of the crisis, in October of 2008, allotments peaked at approximately $250B to the ECB, and approximately $100B to the BOJ. The sharp rise in allotments was due to a move by the Federal Reserve to raise the ceiling on allotment amounts. To construct a global measure of total loans to banks in the Eurozone, Japan and Switzerland. We add the total amounts outstanding for lines extended to the ECB, BOJ and SNB, and TAF loans extended to the Eurozone, Japan and Switzerland.

Following Hasbrouck (1991), we test for the impact of the constructed measure of swap line allotment flows on the covered interest rate parity deviations and order flow for 1 week FX swaps. The selection of the 1 week maturity is consistent with the majority of swap allotments being of 1 week maturity. The multivariate VAR framework is summarized in equations 21, 22 and 23. As well as the measure of CIP deviations CIP_t and order flow OF_t, we augment the bivariate VAR in section 4.2 with a measure of swap allotment flows A_t. The identifying assumption is that shocks to swap line allotments can have contemporaneous effects on the covered interest rate parity deviation and order flow. In contrast, swap line allotments are only affected by lagged order flow and cip deviations. We hypothesize that a positive shock to swap line allotments causes a decline in order flow, as banks substitute toward the swap line for additional dollar funding. Similarly, banks that now receive dollar funding can use their arbitrage capital by supplying dollars in the FX swap market. The decline in order flow then narrows deviations of covered interest rate parity.

$$CIP_t = \alpha_1 + \sum_{k=1}^{L} \gamma_{1,k} CIP_{t-k} + \sum_{k=0}^{L} \beta_{1,k} OF_{t-k} + \sum_{k=0}^{L} \delta_{1,k} A_{t-k} + \epsilon_{1,t} \tag{21}$$

$$OF_t = \alpha_2 + \sum_{k=1}^{L} \gamma_{2,k} CIP_{t-k} + \sum_{k=1}^{L} \beta_{2,k} OF_{t-k} + \sum_{k=0}^{L} \delta_{2,k} A_{t-k} + \epsilon_{2,t} \tag{22}$$

$$A_t = \alpha_3 + \sum_{k=1}^{L} \gamma_{3,k} CIP_{t-k} + \sum_{k=1}^{L} \beta_{3,k} OF_{t-k} + \sum_{k=1}^{L} \delta_{3,k} A_{t-k} + \epsilon_{3,t} \tag{23}$$

In our baseline specification, we use $L = 7$ lags. We document the impulse response to a 1 standard deviation shock in swap line allotment flows in Figure 11. Consistent with our hypothesis, there is a contemporaneous decline in order flow for the euro/$ and yen/$ pairs.x The effect on order flow is strongest for the euro/$. This is intuitive, given the majority of swap line allotments were extended to the ECB, which then auctioned funds to European banks that relied on dollar funding in the euro/$ FX swap market.

Examining price effects, we see that there is a peak narrowing of CIP deviations by 5 basis points for each pair, with the peak effect occurring 2-3 days following the swap line shock. The delayed price adjustment is attributed to the timing of swap line allotments; allotments occur in periods of extreme dislocation in FX swap markets, and are responding to periods of low liquidity, high counterparty risk, and significant dollar shortages. While the effect of swap lines on reducing CIP deviations has been the focus of Bahaj et al. (2018), we contribute to this literature by showing that the price impact of central bank swap lines occurs through the channel of order flow.

6.2 Quarter-end effects

Since 2015, there have been increasing limits to arbitrage in financial markets through regulations on bank leverage. Basel 3 requires a minimum risk-adjusted capital to assets ratio. At quarter-ends, there is an incentive for financial institutions to window-dress balance sheets in order to meet leverage requirements imposed by Basel 3. Quarter-end reporting obligations are known publicly to dealers, and in accordance with our microstructure hypothesis, we find evidence of contemporaneous price-setting in Figure 12, which plots the 1 week CIP deviation for the euro/$, chf/$ and yen/$ pairs. We can see regular spikes in CIP deviations at quarter-ends, stemming from resetting of the forward rate in the FX swap market. The right panel of Figure 12 shows the reaction of the 1 week CIP deviation at the quarter end in September 2016. Contemporaneous adjustment of the forward rate of these contracts prior to one week prior to quarter-end is due principally to the inability of leverage constrained agents from borrowing dollars and supplying those dollars in a FX swap. Once the quarter-end period ends, the forward rate contemporaneously adjusts back to its pre quarter-end level. The spikes in quarter-ends are a post 2015 phenomenon as we summarize dynamics of CIP deviations around all quarter-ends in Table 8. Dividing our sample into pre and post 2015, we observe a significant contemporaneous adjustment of the forward rate in the post 2015 period. Once the FX swap enters the quarter-end period, CIP deviations widen by approximately 35 basis points on average for the euro/$ and yen/$ pairs, and 20 basis points for the chf/$ pair.

Given there is contemporaneous adjustment of the forward rate, we test for whether there are any significant effects on order flow during the quarter-end period. For example, if there is delayed price-setting, we expect to see a significant positive rise in order flow. In equation 24, we test for the sensitivity of the 1 week CIP deviation and order flow in response to the quarter-end adjustment. $Qend_t$ is a dummy variable for quarter ends, and is equal to 1 in the last week of the months of March, June, September and December.[9]Controls X_t include the trade weighted dollar exchange rate, VIX volatility index and the USD libor-ois spread.

$$Y_t = \alpha + \beta Post2015_t + \gamma Qend_t + \delta Qend_t \times Post2015 + X_t + \epsilon_{it} \tag{24}$$

The coefficient of interest in the regression specification is δ which measures the interaction of quarter-ends with the period since 2015 when spikes in CIP deviations are more apparent. The results in Table 9 are for the regression specification in equation 24, with the first 3 columns run for CIP deviations for the euro/$, chf/$ and yen/$ pairs respectively. In line with estimates of contemporaneous CIP adjustment at quarter-ends, we find a sustained widening of CIP deviations during quarter-ends.[10] Columns 4-6 include the order flow effects, which are statistically weak for all pairs. This suggests that dealer pricing is efficient, and are able to price the forward rate in a way that is consistent with minimising order imbalances.

6.3 Monetary Announcements

CIP deviations are decomposed into a forward premium and the interest rate differential. In response to a change in the risk-free rate, we hypothesize that the forward premium reacts in a systematic way to offset the change in the interest rate differential. The dynamics of forward rate adjustment is dependent on the source of information. We argue in this section that as

[9]The beginning of the quarter-end period is typically the 22nd for months with 30 days, and the 23rd for months with 31 days. The reason for this is the convention that a FX swap contract begins 2 days after it is agreed upon. For example, in September, a FX swap trade on 22nd September will begin on the 24th, and expire on the 1st of October.

[10]A concern with estimates of CIP deviations during quarter-ends is that it may be due to time trends or other variables that are unrelated to the quarter-end period. To address this concern, we have a more robust design in Appendix C which reports a regression specification that uses a set of control maturities that are greater than 1 year.

monetary announcements are public information, we expect contemporaneous adjustment in the forward rate. Scheduled monetary announcements of the European Central Bank, Bank of Japan and Swiss National Bank.

In Figure 13, we plot the forward premium of the euro/\$, chf/\$ and yen/\$ in response to scheduled monetary announcements of the ECB, SNB and BOJ. The ECB announcement we consider is the September 14th, 2014 announcement where the ECB lowered the deposit facility rate by 10 basis points.[11]. The SNB policy announcement is on January 15th, 2015, where the interest rate target is lowered by 50 basis points to -0.75%, and the SNB lifts the floor on the Chf/Euro exchange rate.[12] Finally, the BOJ announcement we document is the 29th January, 2016 announcement when the central bank introduces a negative interest rate of 10 basis points on current account that financial institutions hold at the central bank.[13] For each announcement, we observe a widening of the forward premium of approximately a similar magnitude In Figure 13, with most of the adjustment occurring within an intra-day window of the announcement. The increase in the forward premium in response to a decline in the risk-free rate is intuitive: dealers offset the change in the risk-free rate with a change in the forward premium, keeping the CIP deviation constant. We illustrate this hypothesis in equation 25, where a decline in the risk-free rate r_d^f is met by an offsetting increase in the forward premium, preserving the cost of swapping euros into dollars.

$$\Delta = \underbrace{1 + r_{\$}^f}_{\text{direct}} - \underbrace{\frac{F \uparrow}{S}(1 + r_d^f \downarrow)}_{\text{synthetic}} \tag{25}$$

We test the hypothesis in equation 25 more concretely through an event study analysis of scheduled monetary announcements. For our measure of monetary surprises, we calculate the daily change in the announcement as measured by the change in the 1 month overnight index swap (OIS) rate. The surprise rate is a proxy for the surprise component of the interest rate change around monetary announcements based on a measure of the risk-free rate. We run the following event study for days of scheduled announcements, by regressing the change in the CIP deviation and order flow on the surprise measure of interest rates. Our event study results in Table 10 show that monetary announcements have no statistical effect on CIP deviations or order flow. The results are consistent with contemporaneous adjustment of the forward premium as dealers offset changes to the interest rate differential.

[11]See ECB monetary policy decision here: https://www.ecb.europa.eu/press/pr/date/2014/html/pr140904.en.html

[12]see SNB press release here: https://www.snb.ch/en/mmr/reference/pre_20150115/source/pre_20150115.en.pdf

[13]For BOJ press release here: https://www.boj.or.jp/en/announcements/release_2016/k160129a.pdf

7 Conclusion

Price-setting in the FX swap market in periods where covered interest rate parity holds is simple: dealers price the forward rate in a mechanical way to ensure parity of the arbitrage condition. However since 2008 price determination in FX swaps is complicated by heterogeneity in funding spreads, leverage constraints, and other factors inhibiting the free flows of arbitrage capital required to make the CIP condition hold. In periods where price determination is complicated, dealers can use order flow. This measures underlying demand for swapping domestic currencies, such as euros, Swiss francs and yen into dollars.

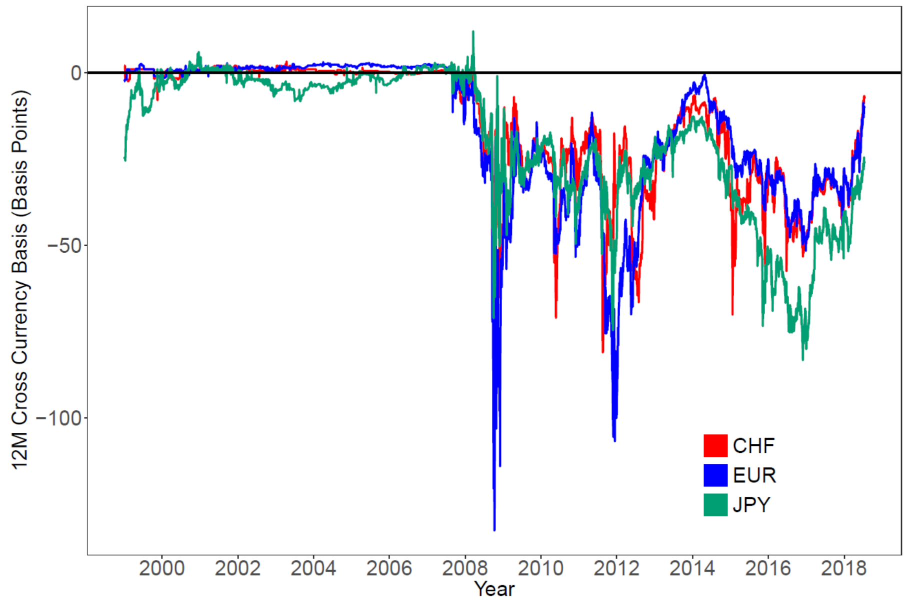
In this paper we detail a new channel for price discovery in FX swap markets. Dealers learn about fundamentals through order flow to update the price of the forward. Through a model framework, we outline a price-setting rule for dealers, where dealers update the forward price to offset changes in order flow. Underpinning the price-setting equation is that dealers are averse to accumulating inventory, and seek to set a forward price that equates customers net demand for dollars in the FX swap market with the supply of dollars of agents with arbitrage capital.

We test the framework empirically, using data on inter-dealer trades from the TR D2000-2 to construct a measure of order flow for 1 week FX swaps. We estimate a price impact of order flow on the order of 5 basis points in response to a 1 standard deviation increase in order flow. The price impact is observed in the post 2008 period, when deviations of covered interest rate parity persist, and is quantitatively more significant in periods of increased heterogeneity of dollar funding spreads, as measured by the range of USD Libor quotes.

We then proceed to take the empirical framework to understand price-setting in the FX swap market in response to shocks to public and private information. We find evidence that the channel of price-setting through order flow occurs in response to a shock to private information. We illustrate this hypothesis with an analysis of central bank swap lines during the financial crisis. Our hypothesis is that the details of which banks draw the swap line are unknown to the inter-dealer market. Therefore, as banks that initially relied on dollar funding via FX swaps now draw liquidity from the swap line, we expect a decline in net demand for pressure for swapping euros, swiss francs and yen into dollars in the FX swap market. Empirically, we find support for the private information view: positive shocks to swap line allotments lead to a decline in order flow and a narrowing of CIP deviations. In contrast, sources of public information, such as monetary announcements and quarter-end reporting obligations, are incorporated into dealer information sets. Using high frequency tick data on forward and spot rates, we document contemporaneous intra-day adjustment of the forward rate as 1 week FX swaps enter the quarter-end period, and in an intra-day window around monetary announcements, supporting the public information view.

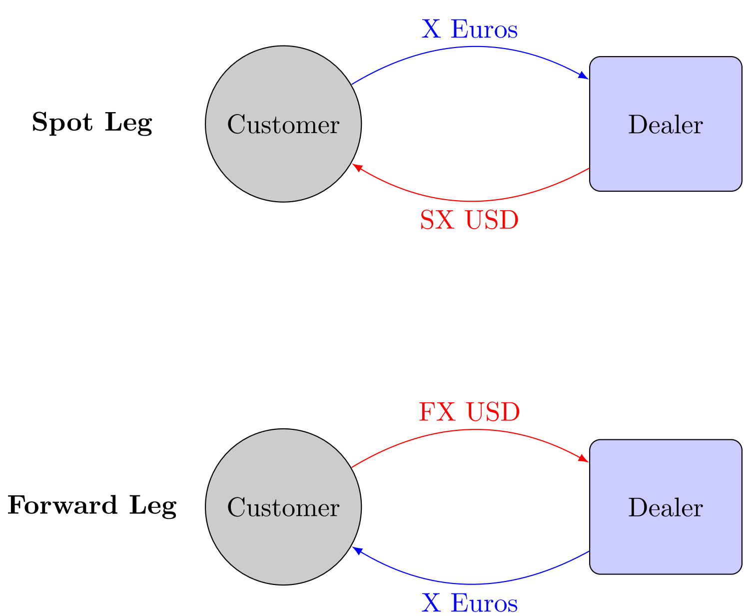
Figures

Figure 1: Covered Interest Rate Parity Deviations for euro/$, yen/$ and chf/$ pairs



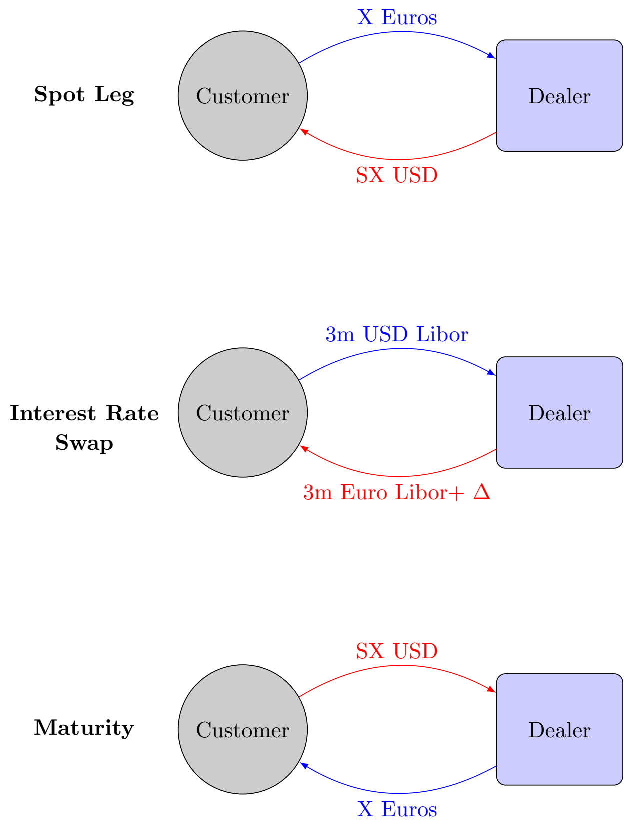
Note: This Figure plots the 12M Cross-Currency Basis measured in basis points, obtained from Bloomberg. This provides a measure of CIP deviations based on a LIBOR benchmark rate. Negative deviations indicate a dollar borrowing premium for the euro/$, chf/$ and yen/$ pairs. Sample period is 01/00-11/18.

Figure 2: Foreign exchange swap



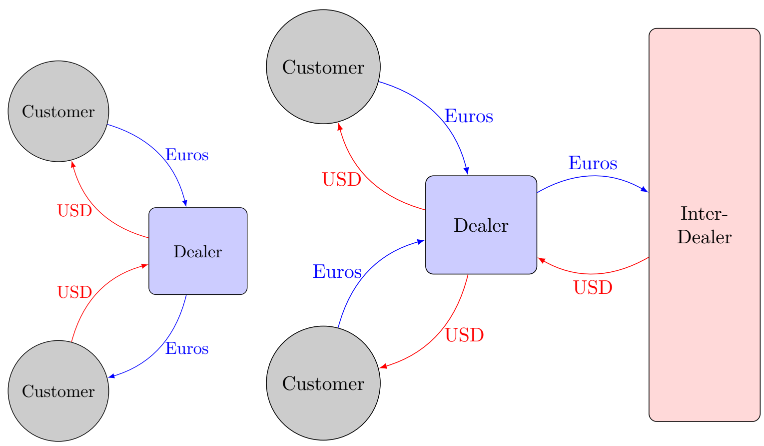
Note: FX swap is typically for maturities at less than 3m. At the spot leg, domestic currency and dollars are swapped at the prevailing spot rate. At maturity, the principals are then re-exchanged at the forward rate.

Figure 3: Cross-currency swap



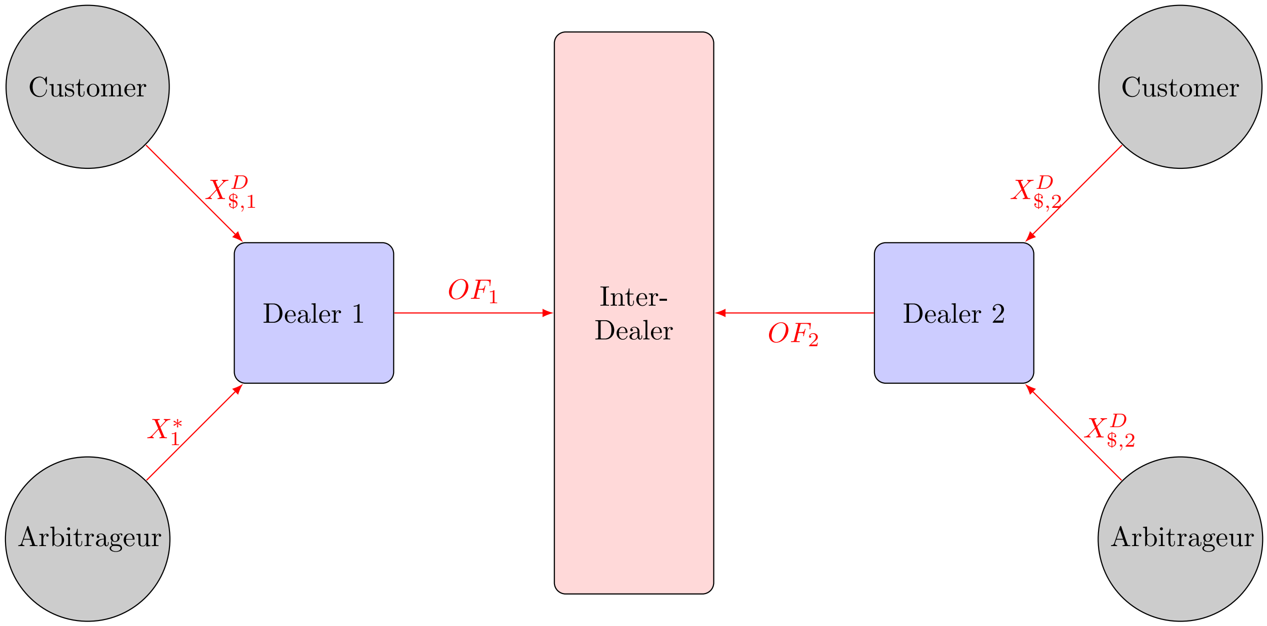
Note: The Cross-Currency Swap is typically for maturities >3m. In the spot leg, dollars are exchanged at spot. The bank and dealer then engages in an interest rate swap, in which the bank pays 3m USD LIBOR, and the dealer pays 3m LIBOR in domestic currency with the addition of the cross-currency basis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

Figure 4: Dealer-Customer Trading in FX Swaps Left: Matched Flows, Right: Unmatched flows go to inter-dealer market



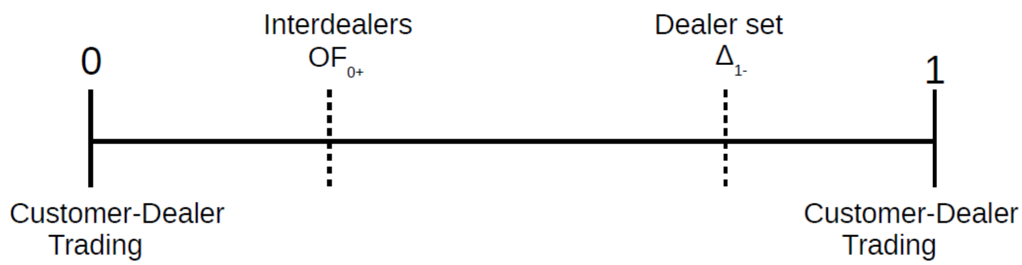
Note: Left: the dealer matches swap of euros to dollars from one customer with swap of dollars to euros from another customer. Right: Both customers swap euros into dollars. The dealer submits excess demands for swapping dollars into euros to the inter-dealer market.

Figure 5: Schematic of the interactions between customers, dealers and the inter-dealer market



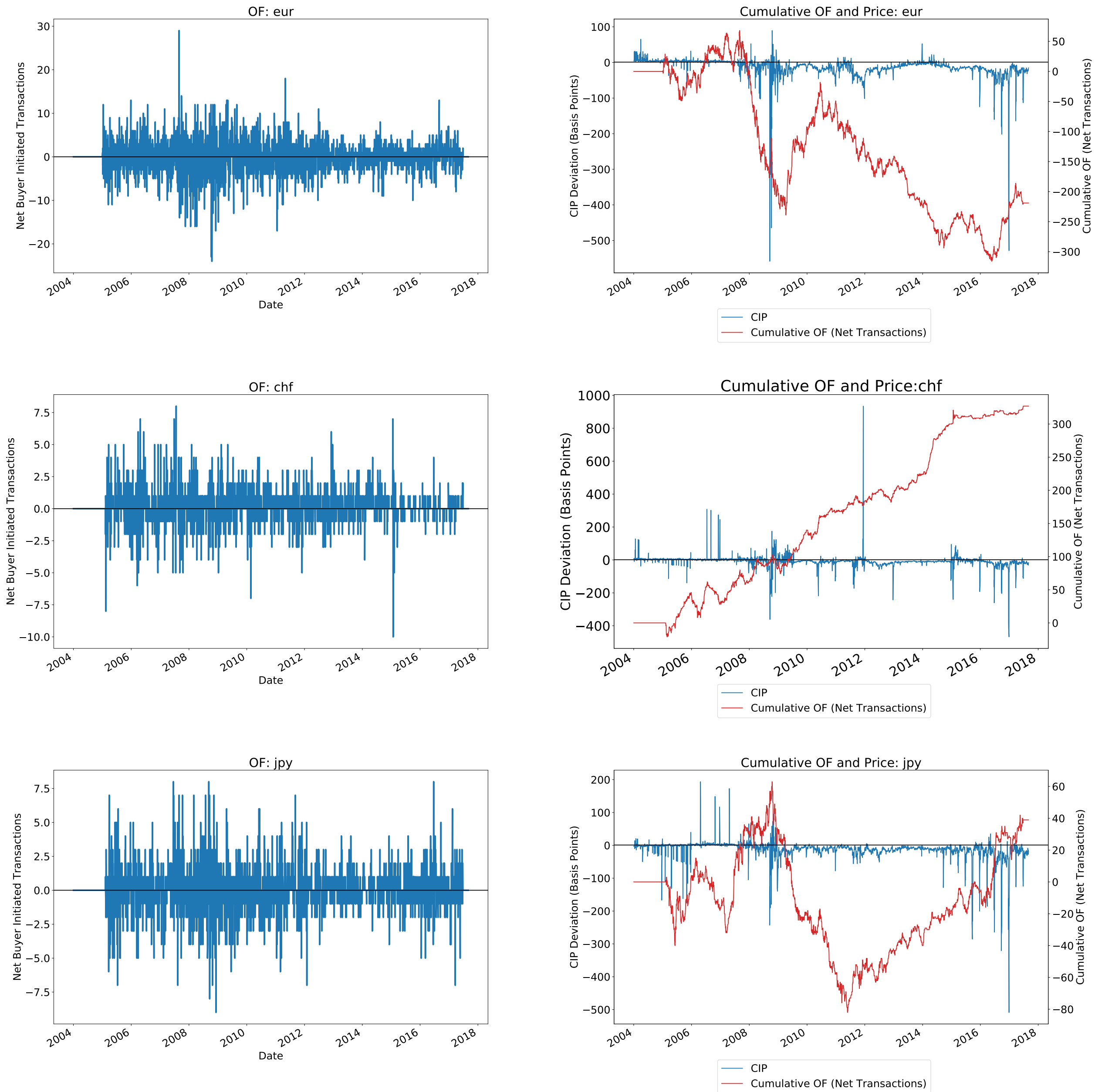
Note: This schematic illustrates the structure of the dealer-customer and inter-dealer market. Each customer has a net demand for dollar funding in the FX swap market, which we denote $x^D_\$$. The excess demands for dollar funding that cannot be met by the dealer's supply of dollars, is in turn submitted to the inter-dealer market. Aggregating net orders for swapping domestic currency into dollars gives rise to inter-dealer order flow OF which is observed as a public signal by the inter-dealer market for setting the forward rate.

Figure 6: Timing



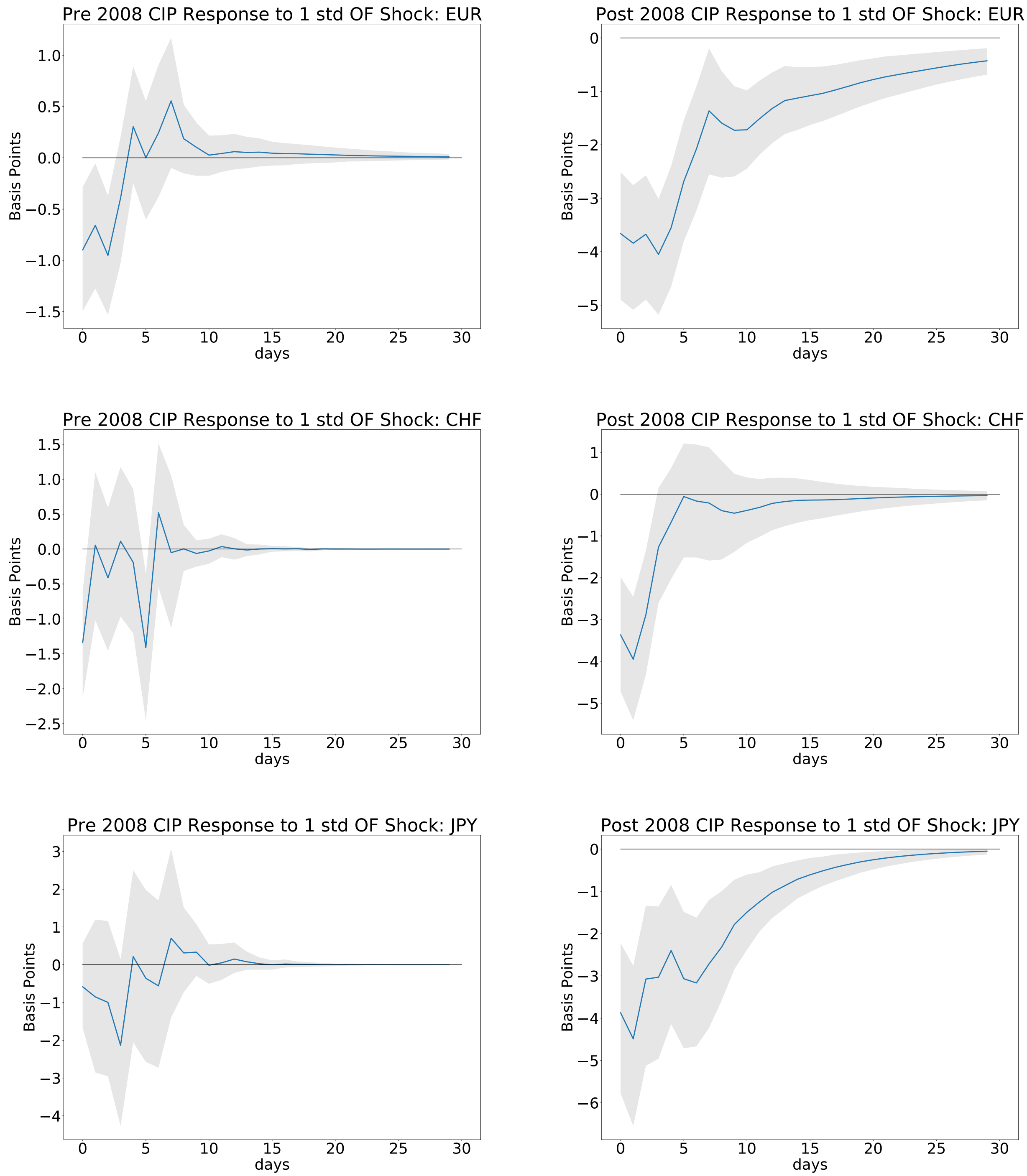
Note: This schematic illustrates the timing of the model. The customer-dealer trading is done at the beginning of each period. Following customer-dealer trading, there is an inter-dealer market which sets the forward price following the customer-dealer trading. Critically, dealers use inter-dealer order flow at the end of the period OF_{t+} in order to set the Δ_{t+1} for the following period.

Figure 7: Daily and Cumulative Order Flow 1 Week count measure- euro/\$, chf/\$ and yen/\$



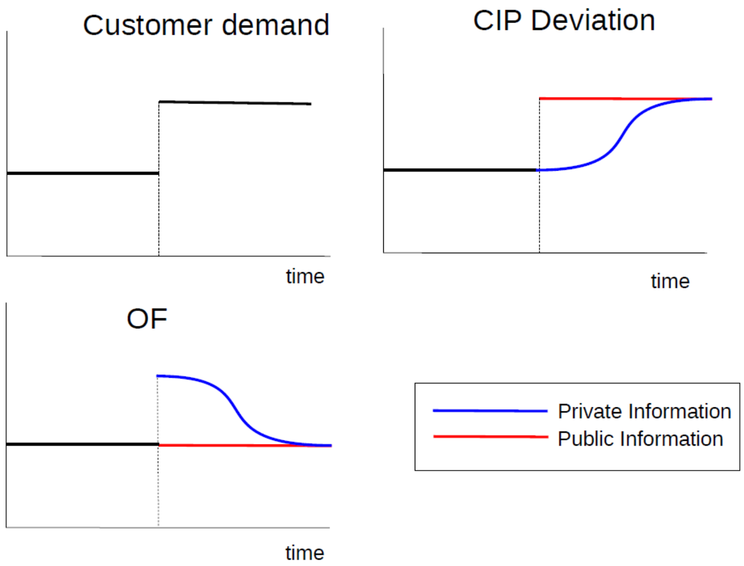
Note: Daily count order flow for euro/\$, yen/\$ and chf/\$ pairs using the TR D2000-2, for FX swap maturities at 1 week. Order flow is given as the net of buyer initiated transactions, where buyer initiated transactions are signed +1 and seller initiated transactions are signed -1. $OF_t^{count} = \sum_{k=t_0}^{k=t} \mathbb{1}[T_k = B] - \mathbb{1}[T_k = S]$

Figure 8: Response of Euro/\$, Yen/\$ and Chf/\$ 1w cross-currency basis to unit shock in count order flow in pre 2008 (left) and post 2008 (right)



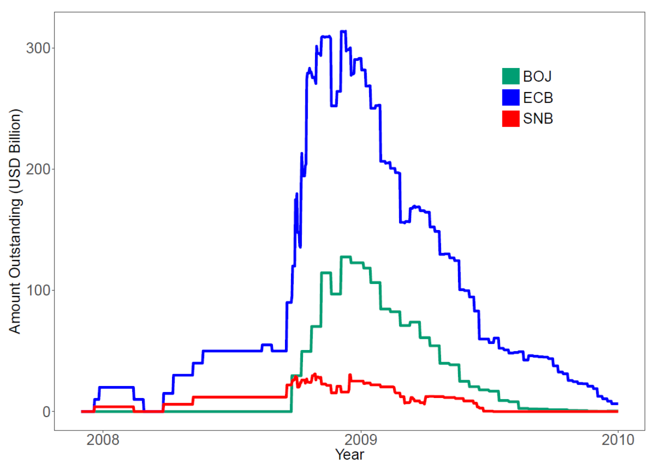
Note: This Figure plots the impulse response of the change in CIP deviations to a 1 standard deviation shock to order flow for 1 week euro/\$, chf/\$ and yen/\$ FX swaps, based on a bivariate VAR following Hasbrouck (1991). Standardized order flow OF is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and CIP deviation is calculated using TR tick history quotes on 1 week forward rates. We condition our sample into two periods based on pre 2008 and a post 2008 period. The left panel shows response of euro/\$, chf/\$ and yen/\$ in the pre-2008 period, and the right panel shows the response in the post-2008 period. Total sample period is from 01/2005-07/2017. Gray area denotes a standard error band equivalent for statistical significance at the 10% level.

Figure 9: Response of order flow and CIP deviations to a shock to customer demands in FX swap market



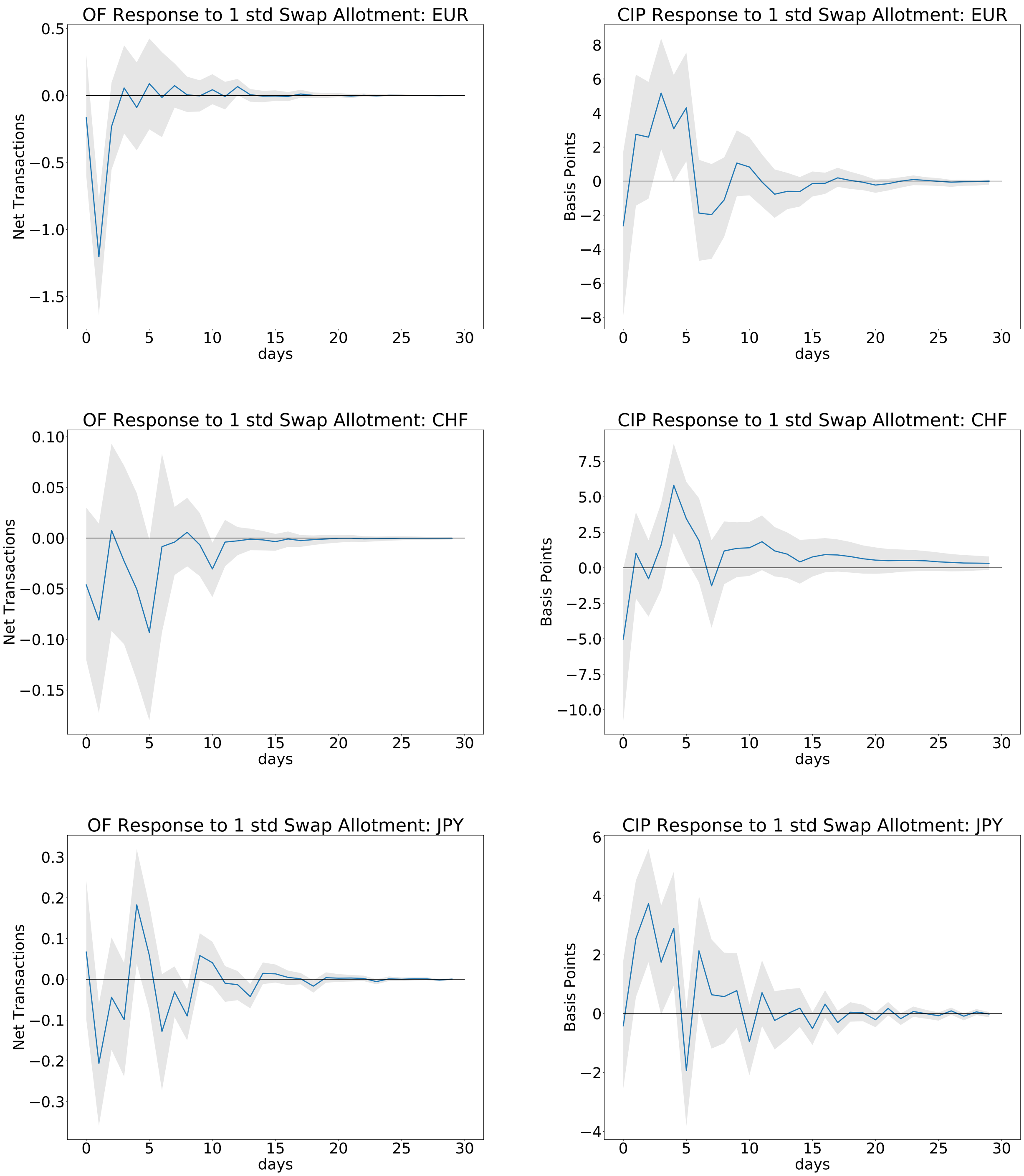
Note: Time series response of order flow and CIP deviations in response to a demand for dollar funding by customers. If the shock is based on private information outside the dealer set, order imbalances rise, and there is a delay in price-setting where dealers raise the forward premium (and hence the cross-currency basis). In contrast, if the shock is public information, then prices adjust contemporaneously and order imbalances remain unchanged.

Figure 10: Loans outstanding: Swap line allotments



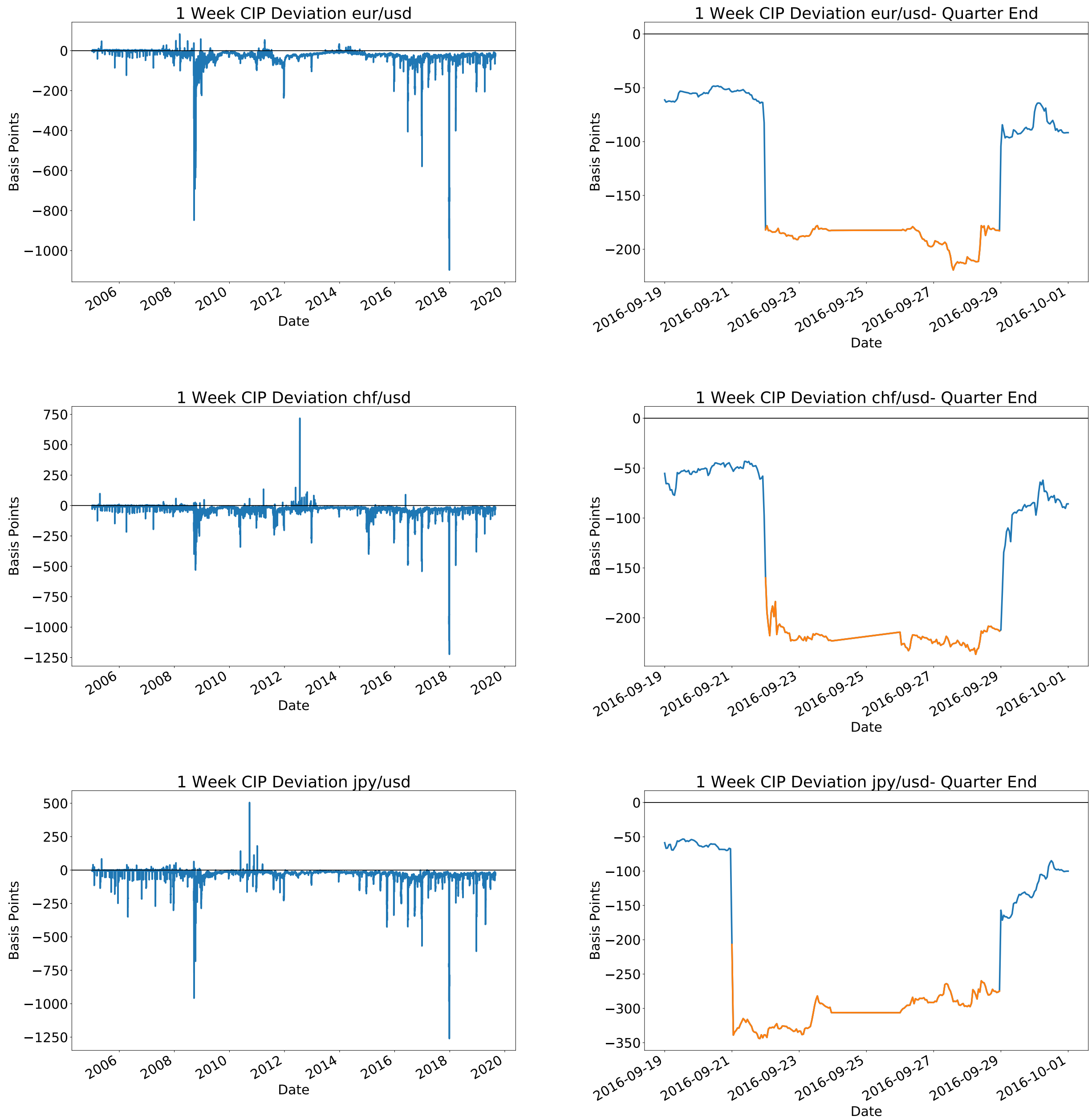
Note: This plots total allotments by the Federal Reserve to counterparty central banks of the ECB, BOJ and SNB in the period 2008-2010. The total allotments outstanding are constructed by aggregating all new loans to each counterparty central bank, less any loans that have matured. Data obtained from the Federal Reserve Board of Governors.

Figure 11: CIP and OF Response to 1 std change in Swap Line Allotments



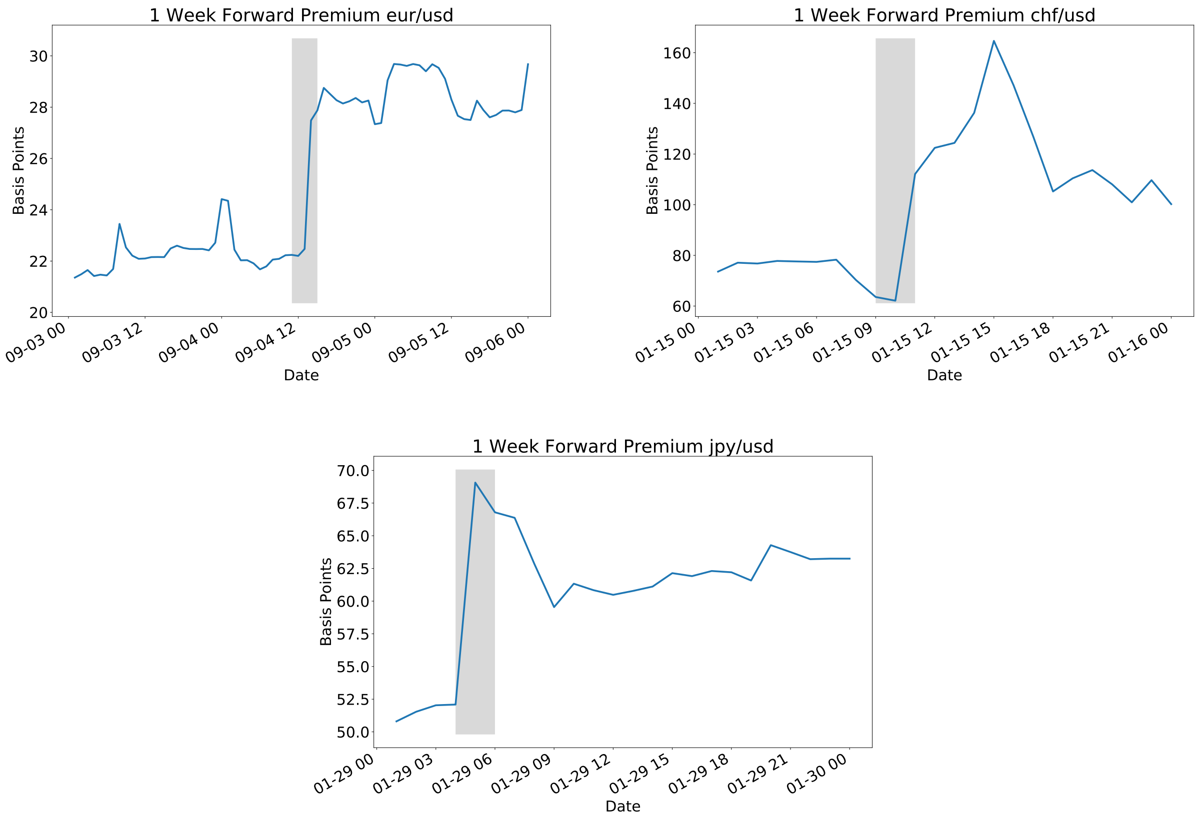
Note: This Figure plots the impulse response of the change in CIP deviations and order flow to a 1 standard deviation shock in swap line allotments for 1 week euro/\$, chf/\$ and yen/\$ FX swaps, based on a multivariate VAR following Hasbrouck (1991). Standardized order flow *OF* is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and CIP deviation is calculated using TR tick history quotes on 1 week forward rates. Swap line allotments measure aggregate flows of dollar loans from the Federal Reserve to counterparty central banks. The left panel shows order flow and the right panel shows the response of cip deviations of euro/\$, chf/\$ and yen/\$ respectively. Total sample period is from 01/2007-12/2011. Gray area denotes a standard error band equivalent for statistical significance at the 10% level.

Figure 12: Left: 1 week euro/$, chf/$ and yen/$ CIP deviations, full sample, Right: 1 week euro/$, chf/$ and yen/$ CIP deviations during quarter-end in September 2016



Note: Left panel: This plot constructs 1 Week CIP Deviations for the euro/$, chf/$ and yen/$ pairs. Right panel: This plot examines 1 week CIP deviations for the euro/$, chf/$ and yen/$ pairs around the quarter-end period in September of 2016, with contemporaneous adjustment of the forward premium as the FX swap contract enters the quarter-end period. The CIP deviation is computed using 1 week forward, spot and domestic and dollar LIBOR rates. The sample period is 2004-2019, using intra-day data from Thomson Reuters Tick History

Figure 13: Response of the forward premium of euro/$, chf/$ and yen/$ pairs to scheduled monetary announcements of the ECB, SNB and BOJ



Note: This plot shows the response of 1 week forward premium in euro/$, chf/$ and yen/$ around scheduled monetary announcements of the ECB, SNB and BOJ respectively. Grey area denotes an intra-day window around the scheduled monetary announcement. In each case, the scheduled announcement changed the central bank policy rate and caused dealers to contemporaneously adjust the forward premium. The forward premium is computed using 1 week forward and spot rates, using intra-day data from Thomson Reuters Tick History

Tables

Table 1: Summary Statistics 1 Week CIP Deviations.

	Pre 2008				Post 2008			
	mean	sd	min	max	mean	sd	min	max
Euro/$	-2.33	10.3	-120.0	5.1	-28.5	38.7	-621.9	73.1
Chf/$	-8.1	17.0	-213.3	10.3	-34.0	42.7	-500.6	54.9
Yen/$	-11.6	37.5	-347.2	33.7	-31.9	45.4	-705.8	52.7

Note: This table records summary statistics of CIP deviations in euro/$, chf/$ and yen/$ for 1 Week FX swaps. CIP deviations are expressed in basis points. Data on 1 Week Forward and Spot rates are taken from TR Tick History. Interest rates are 1 Week Libor. The full sample period is from 01/2005-09/2019, and is divided into pre and post 2008 periods.

Table 2: Summary Statistics count Order Flow.

	Pre 2008				Post 2008			
	mean	sd	min	max	mean	sd	min	max
Euro/$	-.003	3.91	-16	29	-.07	3.42	-24	29
Chf/$	0.08	1.59	-8	8	0.10	1.17	-10	8
Yen/$	0.06	1.63	-7	8	0.015	1.46	-9	8

Note: This table records summary statistics of order flow based on trades in 1 week FX swaps using inter-dealer trades in Thomson Reuters D2000-2 Platform. Order flow is constructed as the net of buyer initiated transactions, where a transaction is signed +1 if it is swapping euros, swiss francs and yen into dollars at the spot leg of the FX swap contract. The Lee-Ready algorithm is used to sign the transactions using bid and ask quotes. The sample period is from 01/2005-07/2017.

Table 3: Price Impact of Order Flow for 1 Week FX swaps, conditioning on pre and post 2008 periods

	(1)	(2)	(3)	(4)	(5)	(6)
	ΔCIP_{euro}	ΔCIP_{euro}	ΔCIP_{chf}	ΔCIP_{chf}	ΔCIP_{yen}	ΔCIP_{yen}
OF	-1.232***	-3.474***	-1.679***	-3.078***	-1.490	-4.723***
	(0.468)	(1.002)	(0.646)	(0.987)	(1.055)	(1.447)
Constant	-10.77	10.18	-8.417	13.24	-34.61	2.238
	(21.10)	(11.30)	(38.48)	(12.42)	(78.88)	(8.026)
Observations	583	1,889	578	1,891	522	1,888
R-squared	0.012	0.028	0.006	0.015	0.004	0.038
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Post2008	No	Yes	No	Yes	No	Yes

Note: This table regresses the change in CIP deviations on order flow for 1 week euro/$, chf/$ and yen/$ FX swaps. CIP deviations are expressed in basis points. Standardized order flow OF is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and CIP deviation is calculated using TR tick history quotes on 1 week forward rates. We condition our sample into two periods based on pre 2008 and a post 2008 period. Columns 1, 3 and 5 test condition on the pre 2008 period, columns 2,4 and 6 condition on the post 2008 period. CIP deviation is calculated using TR tick history quotes on 1 week forward rates. Controls include the USD libor-ois spread, the VIX index, and the USD Trade weighted exchange rate. Sample period is from 01/2005-07/2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.

Table 4: Price Impact of Order Flow for 1 Week FX swaps, effects on the forward premium and the interest rate differential

	(1)	(2)	(3)	(4)	(5)	(6)
	Δfp_{euro}	Δird_{euro}	Δfp_{chf}	Δird_{chf}	Δfp_{yen}	Δird_{yen}
OF	3.736***	0.262	3.286***	0.206	5.329***	0.603***
	(1.075)	(0.186)	(0.991)	(0.241)	(1.618)	(0.227)
Constant	-15.33	-5.153***	-22.64*	-9.382***	-3.866	-1.628
	(11.69)	(1.810)	(12.74)	(2.879)	(8.264)	(1.463)
Observations	1,889	1,890	1,891	1,897	1,888	1,898
R-squared	0.031	0.016	0.020	0.029	0.043	0.043
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Post2008	Yes	Yes	Yes	Yes	Yes	Yes

Note: This table decomposes the 1 week cip deviation into the forward premium and the interest rate differential, and regresses the change in the forward premium and the change in the interest rate differential on order flow for 1 week euro/\$, chf/\$ and yen/\$ FX swaps. CIP deviations are expressed in basis points. Standardized order flow OF is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and the forward premium is calculated using TR tick history quotes on 1 week forward rates. Columns 1, 3 and 5 test the forward premium, and columns 2,4 and 6 test for effects on the 1 week libor interest rate differential, for the euro/\$, chf/\$ and yen/\$ pairs respectively. Sample period is from 01/2008-07/2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.

Table 5: Price Impact of Order Flow for 1 Week FX swaps

	(1)	(2)	(3)	(4)	(5)	(6)
	ΔCIP_{euro}	ΔCIP_{euro}	ΔCIP_{chf}	ΔCIP_{chf}	ΔCIP_{yen}	ΔCIP_{yen}
OF	-1.537***	-3.652***	-1.293***	-4.594***	-1.108**	-5.047***
	(0.309)	(1.051)	(0.459)	(1.619)	(0.558)	(1.588)
Constant	-0.0445	14.44	10.42	10.94	0.323	-1.325
	(4.528)	(17.04)	(8.503)	(14.26)	(10.78)	(10.46)
Observations	1,223	1,251	1,223	1,256	1,171	1,261
R-squared	0.025	0.022	0.007	0.017	0.002	0.032
Controls	Yes	Yes	Yes	Yes	Yes	Yes
libor range	<0.1%	>0.1%	<0.1%	>0.1%	<0.1%	>0.1%

Note: This table regresses the change in CIP deviations on order flow for 1 week euro/$, chf/$ and yen/$ FX swaps. Standardized order flow OF is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and CIP deviation is calculated using TR tick history quotes on 1 week forward rates. We condition our sample into two periods based on the range of libor-usd bank quotes which we use as a proxy for heterogeneity in funding spreads in borrowing dollars. Columns 1, 3 and 5 test condition on days when the range in libor quotes is less than 0.1%, columns 2,4 and 6 condition on days when the range in libor quotes is greater than 0.1%. Sample period is from 01/2005-07/2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.

Table 6: Price Impact of Order Flow for 1 Week FX swaps

	(1)	(2)	(3)
	ΔCIP_{euro}	ΔCIP_{chf}	ΔCIP_{yen}
OF	-3.437***	-2.026**	-3.909***
	(1.189)	(0.791)	(1.247)
post2015	0.646	-3.308	2.008
	(2.931)	(3.441)	(3.111)
Qend	-10.28***	-11.07***	-6.097
	(3.287)	(4.282)	(4.533)
OF $\times post2015$	0.859	0.518	2.381
	(1.952)	(2.562)	(1.553)
OF $\times Qend$	2.254	-8.184	-14.32
	(2.779)	(5.940)	(12.04)
OF $\times Qend \times post2015$	-12.34	-14.51	-9.195
	(18.84)	(11.91)	(28.55)
Constant	13.28	2.925	8.782
	(21.10)	(18.27)	(13.96)
Observations	1,889	1,891	1,888
R-squared	0.045	0.050	0.077
Controls	Yes	Yes	Yes
Post2008	Yes	Yes	Yes

Note: This table regresses the change in CIP deviations on order flow for 1 week euro/$, chf/$ and yen/$ FX swaps. Standardized order flow OF is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and CIP deviation is calculated using TR tick history quotes on 1 week forward rates. $Qend$ is the quarter-end period, and is formally the last week of the period before quarter-end reporting obligations on the first of the months of March, June, September and December. $post2015$ is a dummy for the post 2015 period. The coefficient on $OF \times Qend \times post2015$ is a triple interaction term that measures the additional price impact of order flow during quarter-end periods in post 2015. Sample period is from 01/2008-07/2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.

Table 7: Price Impact of Order Flow for 1 Week FX swaps

	(1)	(2)	(3)
	ΔCIP_{euro}	ΔCIP_{chf}	ΔCIP_{yen}
$\mathbb{1}[MP_t]$	2.016	-5.608	-8.062**
	(1.637)	(3.818)	(3.520)
OF	-3.709***	-3.100***	-3.711***
	(0.879)	(0.981)	(1.288)
OF $\times 1[\text{MP}_t]$	5.907	-0.137	-13.92
	(4.485)	(3.093)	(10.22)
Constant	-0.443	0.220	0.138
	(0.569)	(0.585)	(0.550)
Observations	1,922	1,926	1,922
R-squared	0.026	0.014	0.062
Post2008	Yes	Yes	Yes

Note: This table regresses the change in CIP deviations on order flow for 1 week euro/$, chf/$ and yen/$ FX swaps. Standardized order flow OF is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and CIP deviation is calculated using TR tick history quotes on 1 week forward rates. $\mathbb{1}[MP_t]$ is a dummy for scheduled announcements of the ECB, SNB and BOJ for columns 1, 2 and 3 respectively. The coefficient on $OF \times \mathbb{1}[MP_t]$ is an interaction term that measures the additional price impact of order flow during scheduled monetary announcements. Sample period is from 01/2005-07/2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.

Table 8: Contemporaneous change in 1 Week CIP deviations as contracts enter quarter-end period.

			Pre 2015	01/2008-12/14				
Pair	count	mean	std	min	25%	50%	75%	max
eur/$	32.0	-0.533	4.502	-14.706	-1.064	-0.237	0.59	10.794
chf/$	32.0	1.696	14.124	-20.247	-3.056	-0.221	2.342	69.064
yen/$	32.0	-11.899	34.559	-152.862	-2.169	-0.285	0.007	16.774
			Post 2015	01/15-09/19				
Pair	count	mean	std	min	25%	50%	75%	max
eur/$	18.0	-36.113	53.794	-148.041	-70.197	-4.021	0.00	7.445
chf/$	18.0	-21.207	53.006	-216.657	-24.549	-3.548	0.000	30.929
yen/$	18.0	-34.575	60.159	-176.062	-77.607	-0.249	1.739	41.804

Note: The table reports summary statistics of the contemporaneous change in CIP deviations for the 1 Week euro/$, chf/$, yen/$ pairs during the quarter-end periods. The quarter-end period is formally the last week of the period before quarter-end reporting obligations on the first of the months of March, June, September and December All summary stats are expressed in basis points. The contemporaneous change in CIP deviations is measured as $CIP_{t,qend} - CIP_{t-1,qend}$, where t measures the time at which 1 week FX swap contracts expire at quarter-ends (beginning of months of March, June, September and December). Data on 1 week forward and spot rates, and Libor interest rates to construct CIP deviations is from TR Tick History.

Table 9: CIP and Order Flow, response of 1 week Deviations to quarter-ends

	(1)	(2)	(3)	(4)	(5)	(6)
	CIP_{euro}	OF_{chf}	CIP_{yen}	OF_{euro}	CIP_{chf}	OF_{yen}
Qend	-14.71***	0.536	-11.80***	0.134	-35.83***	0.0231
	(3.282)	(0.340)	(3.084)	(0.0967)	(4.904)	(0.134)
post2015	-23.72***	-0.360	-17.36***	-0.138	-18.55***	0.294*
	(3.603)	(0.415)	(4.908)	(0.130)	(3.233)	(0.172)
Qend $\times post$2015	-58.39***	-0.492	-69.94***	-0.0463	-142.6***	0.147
	(12.24)	(0.568)	(14.36)	(0.151)	(16.06)	(0.226)
Constant	-43.52*	-3.033	-36.49	0.0270	-22.34	1.032
	(22.20)	(2.129)	(23.37)	(0.543)	(15.56)	(0.772)
Observations	2,361	2,362	2,361	2,365	2,360	2,366
R-squared	0.394	0.007	0.284	0.004	0.519	0.004

Note: This table regresses CIP deviations and order flow for 1 week euro/$, chf/$ and yen/$ FX swaps relative to a set of long term maturities, against a post2015 dummy and an interaction of quarter-ends with the post 2015 dummy Qend × post2015 *Qend* is a dummy indicating the week prior to quarter-ends, and tests for the effect of bank regulations tightening leverage on CIP deviations. Standardized order flow OF is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and CIP deviation is calculated using TR tick history quotes on 1 week forward rates. Controls include the USD libor-ois spread, the VIX index, and the USD Trade weighted exchange rate. Sample period is from 01/2008-07/2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.

Table 10: CIP and Order Flow, event study responses around scheduled monetary announcements of the ECB, SNB and BOJ

	(1)	(2)	(3)	(4)	(5)	(6)
	ΔCIP_{euro}	OF_{euro}	ΔCIP_{chf}	OF_{chf}	ΔCIP_{yen}	OF_{yen}
Δi_{ois}	0.346	-0.0224	0.894	-0.0262	-23.48*	0.171*
	(0.377)	(0.0223)	(0.719)	(0.0227)	(13.19)	(0.0916)
Constant	4.093	-0.298	7.207	-0.0509	-11.99*	0.0106
	(2.968)	(0.231)	(4.576)	(0.139)	(6.899)	(0.140)
Observations	100	102	43	43	82	117
R-squared	0.007	0.004	0.038	0.036	0.042	0.021
Post2008	Yes	Yes	Yes	Yes	Yes	Yes

Note: This table regresses changes in CIP deviations and order flow for 1 week euro/\$, chf/\$ and yen/\$ FX swaps against a series of scheduled monetary announcements of the ECB, SNB and BOJ respectively. Columns 1, 3 and 5 measure the outcome variable as the daily change in the CIP deviation around the monetary announcement, measured as $CIP_{t+1} - CIP_{t-1}$ where t is the day of announcement. Columns 2, 4 and 6 are standardized order flow measured on announcement days. Standardized Order flow OF is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades, and the CIP deviation is calculated using TR tick history quotes on 1 week forward rates. Sample period is from 01/2008-07/2017. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.

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Appendices

A: Order Flow data: Cross-Currency Swaps

This section documents summary statistics and plots of order flow using data from the swap repository facility available at Bloomberg (SDR), which records real-time transactions of cross-currency swap transactions with maturities of greater than 3 months. This dataset includes the tick-level timestamp of the trade, the currencies delivered at the spot and maturity legs of the Swap, and the cross-currency basis of the Swap, which is the measure of the CIP deviation for the swap.[14]. We match transactions using the algorithm in Lee and Ready (1991). The per cent of buyer initiated transactions and matching rates are provided in Table 11, and summary statistics on both count and volume order flow for 1Y, 2Y, 5Y and 10Y swaps in Table 12. Not all trades are successfully matched, as in some cases the transaction price is at the midpoint of the bid-ask. We omit these trades in classifying buyer and seller initiated trades. Although this amounts to a measurement error, the number of matched trades is at least 80% of total trades for all currency-tenor pairs.

Table 11: Trade counts and % buyer initiated for Cross-Currency Swaps,

	1Y			2Y			5Y			10Y		
Pair	N	N_m	%BI	N	N_m	%BI	N	N_m	%BI	N	N_m	%BI
Chf/$	264	256	63%	269	246	54%	338	310	47%	260	238	48%
Euro/$	2187	1932	64%	2828	2310	47%	3352	2623	45%	3480	2761	48%
Yen/$	4429	3734	61%	4423	3532	53%	2815	2310	48%	2179	1777	47%

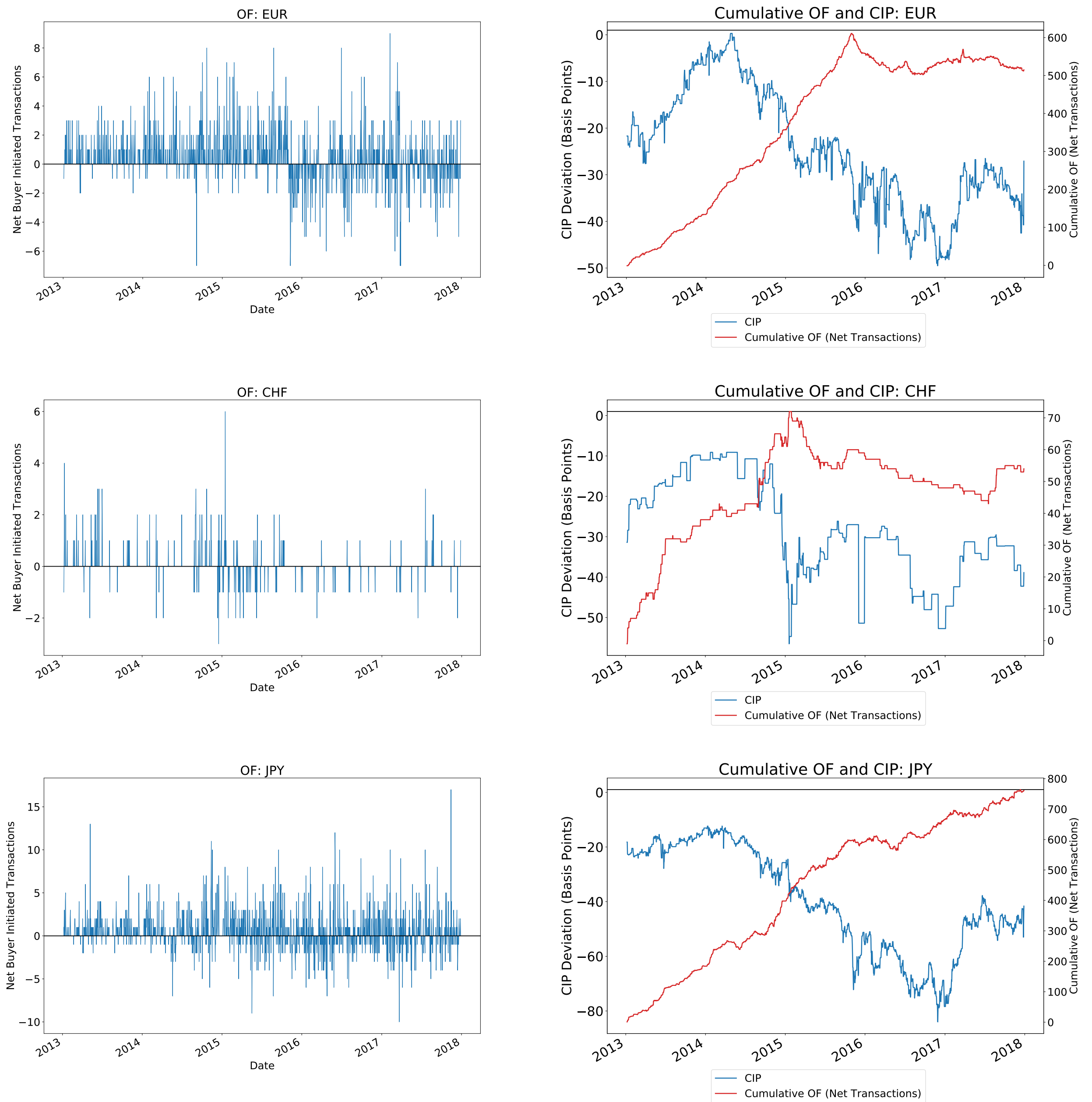
Note: using Lee-Ready algorithm for matching. Trade count (N) is total number of trades recorded for each currency pair and tenor from beginning of sample in 2013. N_m is the number of trades matched using Lee-Ready algorithm. %BI is the per cent of matched trades that are buyer initiated.

[14] For details on how the cross-currency swap works, please refer to Section 2

Table 12: Summary Statistics of daily Count and Volume Order Flow, using SDR data on cross-currency swaps for tenors 1Y, 2Y, 5Y and 10Y

1 Year								
	Count				Volume (Billions USD)			
Pair	mean	sd	min	max	mean	sd	min	max
Chf/$	0.34	1.51	-3	6	0.05	0.22	-0.46	0.69
Euro/$	0.67	2.21	-7	9	0.15	0.61	-2.85	2.17
Yen/$	0.77	2.74	-10	17	0.16	0.61	-2.02	4.33
2 Year								
	Count				Volume (Billions USD)			
Pair	mean	sd	min	max	mean	sd	min	max
Chf/$	0.12	1.43	-4	4	0.02	0.16	-0.36	0.51
Euro/$	-0.17	2.11	-15	7	-0.01	0.38	-2.08	1.48
Yen/$	0.17	2.51	-16	12	0.04	0.33	-1.18	2.02
5 Year								
	Count				Volume (Billions USD)			
Pair	mean	sd	min	max	mean	sd	min	max
Chf/$	-0.09	1.52	-3	5	0.00	0.10	-0.25	0.25
Euro/$	-0.25	2.07	-12	8	0.03	0.23	-1.39	0.98
Yen/$	-0.13	2.05	-14	9	0.00	0.16	-0.70	0.98
10 Year								
	Count				Volume (Billions USD)			
Pair	mean	sd	min	max	mean	sd	min	max
Chf/$	-0.08	1.34	-5	3	0.00	0.06	-0.34	0.11
Euro/$	-0.12	2.13	-8	17	0.00	0.15	-0.63	1.52
Yen/$	-0.13	1.96	-11	17	0.01	0.07	-0.41	0.41

Figure 14: Daily and Cumulative Order Flow for 1 Year Cross Currency Swap ,euro/\$, chf/\$ and yen/\$



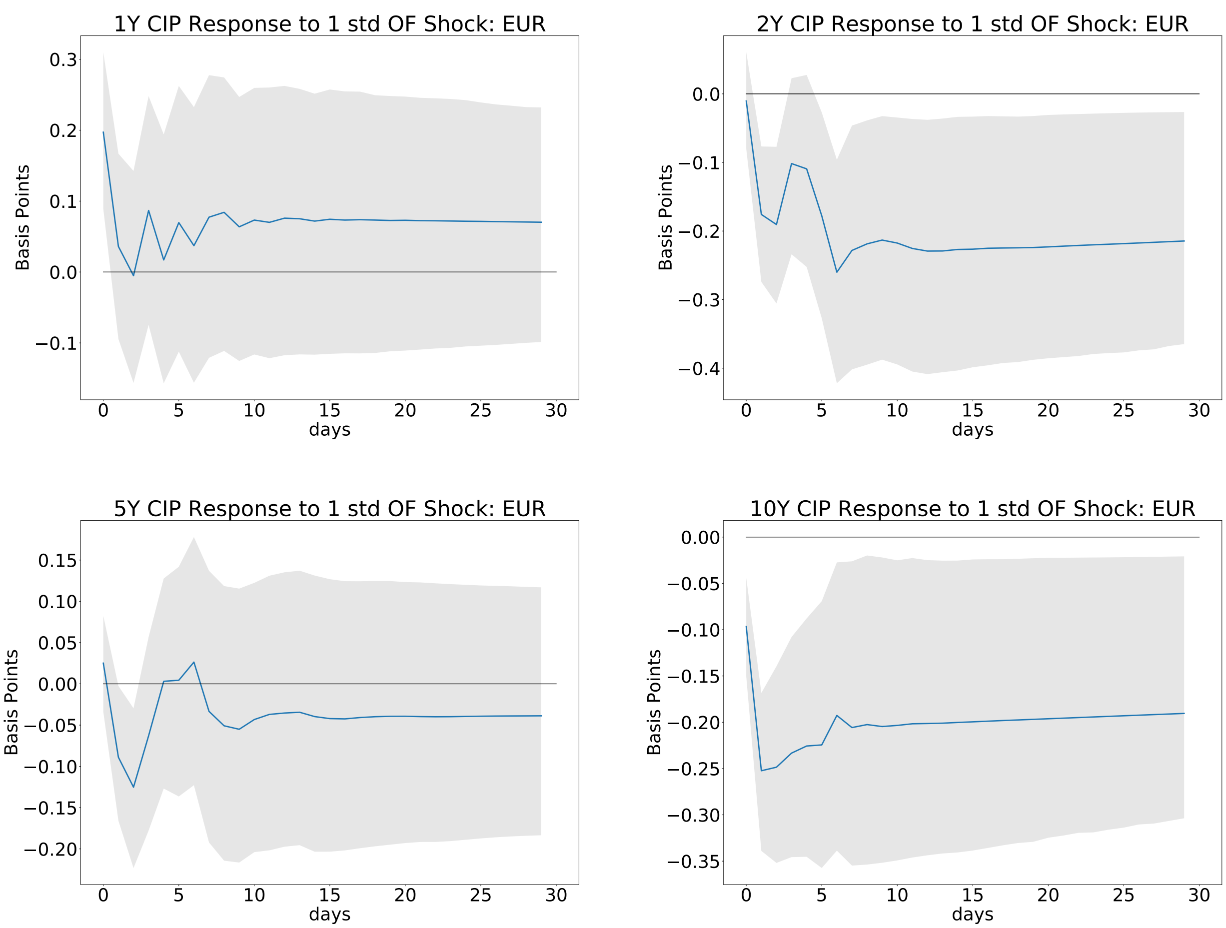
Note: Daily count order flow for euro/\$, yen/\$ and chf/\$ pairs using the Bloomberg Swap Repository, for FX swap maturities at 1 Year. Order flow is given as the net of buyer initiated transactions, where buyer initiated transactions are signed +1 and seller initiated transactions are signed -1. $OF_t^{count} = \sum_{k=t_0}^{k=t} \mathbb{1}[T_k = B] - \mathbb{1}[T_k = S]$

B: Price Impact of Order Flow: Cross-Currency Swaps

We plot the impulse response of the cross-currency basis to a 1 standard deviation shock in order flow for cross-currency swaps at the horizons of 1 year, 2 years, 5 years and 10 years.

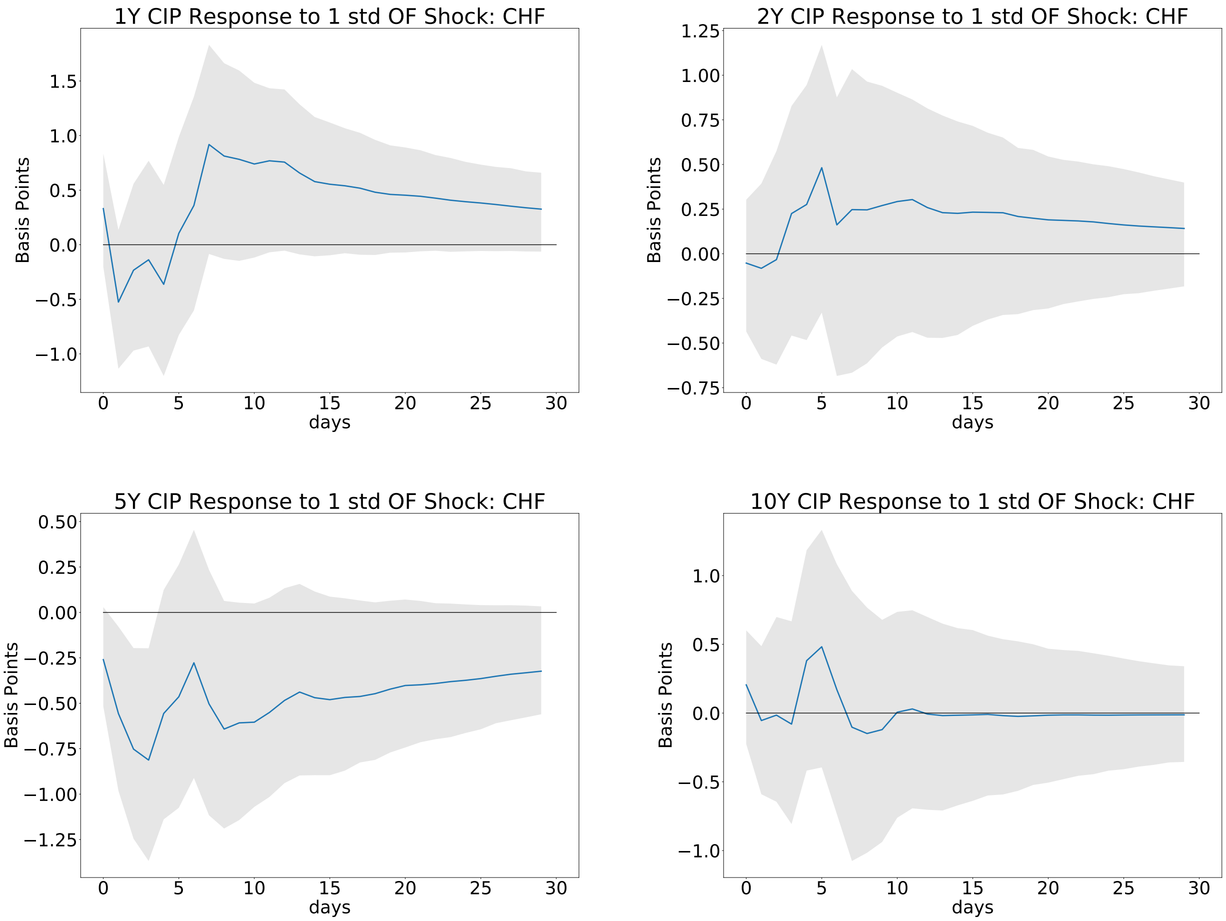
Results are presented for the euro/$, chf/$ and yen/$ pairs in Figures 15, 16 and 17. In Figure 15, we find significant effects of order flow on CIP deviations for the 2Y, 5Y and 10Y tenors, with a peak effect of 0.25 basis points. Similar results are shown in Figure 17, with a widening of the basis for all 4 tenors and a peak widening of the basis by 0.2 basis points, peaking at approximately 4 days after the shock. There is, however, a weak systematic effect on the chf/$ cross-currency basis. The results are consistent with the hypothesis that an unexpected rise in order flow imbalances cause dealers to raise the premium at which domestic currency is swapped into dollars, widening the cross-currency basis.

Figure 15: Response of Euro/$ 1Y cross-currency basis to 1 std shock in order flow



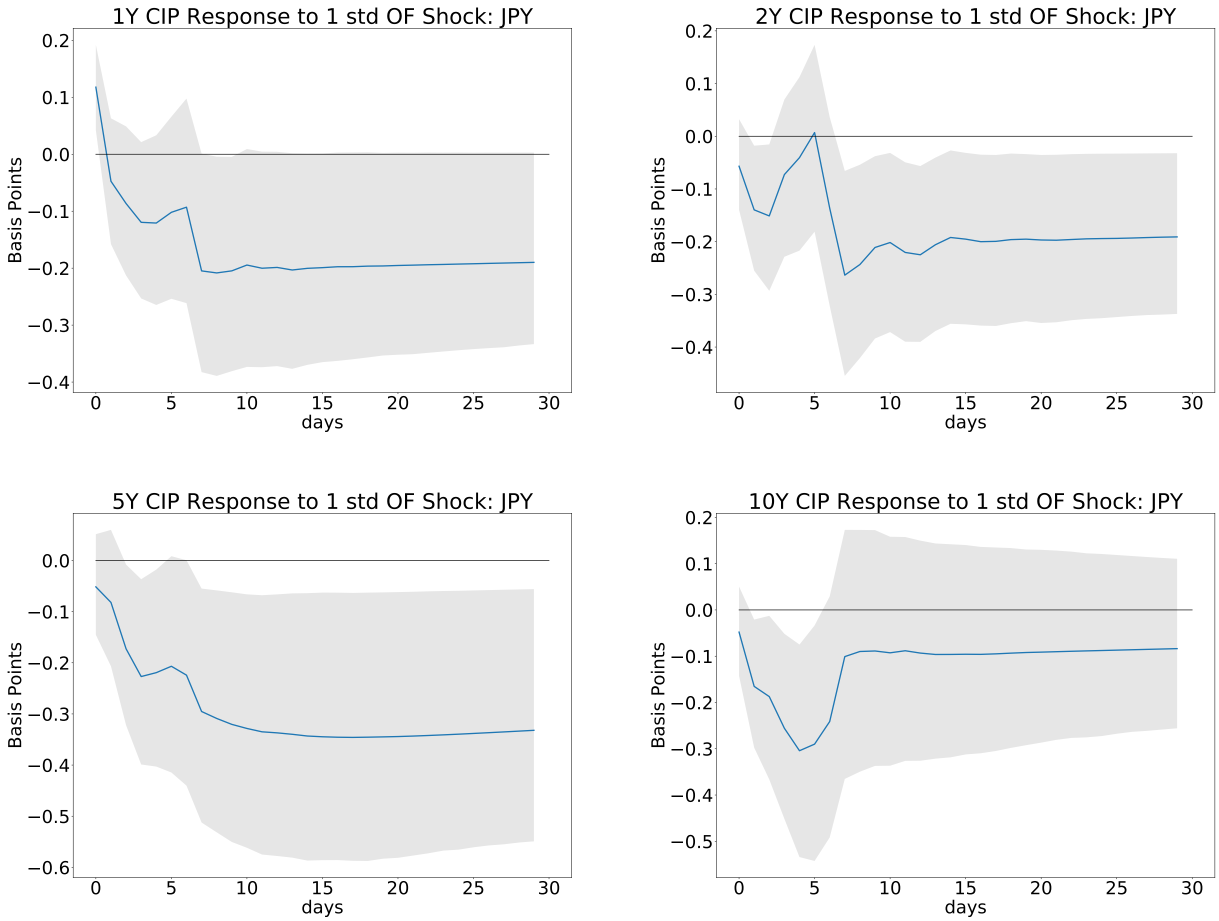
Note: This Figure plots the impulse response of the change in CIP deviations to a 1 standard deviation shock to order flow for 1Y, 2Y, 5Y and 10Y euro/$ cross-currency swap based on a bivariate VAR following Hasbrouck (1991). Standardized order flow OF is measuring the net buyer transactions of swapping euros into dollars, and is sourced from Bloomberg Swap Repository. Total sample period is from 01/2013-12/2018. Gray area denotes a standard error band equivalent for statistical significance at the 10% level.

Figure 16: Response of Chf/\$ 1Y cross-currency basis to 1 std shock in order flow



Note: This Figure plots the impulse response of the change in CIP deviations to a 1 standard deviation shock to order flow for 1Y, 2Y, 5Y and 10Y chf/\$ cross-currency swap based on a bivariate VAR following Hasbrouck (1991). Standardized order flow OF is measuring the net buyer transactions of swapping swiss francs into dollars, and is sourced from Bloomberg Swap Repository. Total sample period is from 01/2013-12/2018. Gray area denotes a standard error band equivalent for statistical significance at the 10% level.

Figure 17: Response of Yen/\$ 1Y cross-currency basis to 1 std shock in order flow



Note: This Figure plots the impulse response of the change in CIP deviations to a 1 standard deviation shock to order flow for 1Y, 2Y, 5Y and 10Y yen/\$ cross-currency swap based on a bivariate VAR following Hasbrouck (1991). Standardized order flow OF is measuring the net buyer transactions of swapping yen into dollars, and is sourced from Bloomberg Swap Repository. Total sample period is from 01/2013-12/2018. Gray area denotes a standard error band equivalent for statistical significance at the 10% level.

C: CIP Deviations around Quarter-Ends: Control-Treatment Design

We now follow Du et al. (2018) and test for quarter-end effects through a control-treatment design. Under the identifying assumption that quarter-end regulations affect dollar funding in the FX swap market at short maturities, we use a set of control maturities >= 1 Year. [15] We run a panel differences-in-differences specification including maturities at a 1 week and a set of control maturities.

[15] Control maturities selected are 1y, 2y, 3y, 4y, 5y, 7y and 10y. We choose these maturities as they account for approximately 60% of trades in Cross-Currency Swaps based on the Bloomberg Swap repository.

$$CIP_{it} = \alpha_i + \gamma Post2015_t + \theta\left[Qend \times Post2015\right]_t + \delta\left[Qend \times Post2015 \times \mathbb{1}[1w]\right]_{it} + X_t + \epsilon_{it} \quad (26)$$

The identifying assumption of the design is that at one week prior to quarter-ends, agents supplying dollars in the FX swap market have an incentive to window dress their balance sheets to reduce leverage in accordance with Basel 3 requirements. In contrast, arbitrage capital for FX swaps at longer-term maturities (>= 1 Year) will be relatively unaffected. To capture the treatment effect in the specification, we interact our quarter-end dummy with the post 2015 period, this is a variable $\mathbb{1}[1w]$ which equals one for the treatment maturity of 1 week FX swaps, and 0 otherwise. Using this approach, the results in Table 13 confirm the hypothesis that CIP deviations are much wider for 1 week FX swaps at quarter ends. Columns 1,2 and 3 test the effects on CIP deviations for the euro/$, chf/$ and yen/$ pairs. The coefficient on the treatment effect suggests 1 week deviations are 40 basis points wider during the week end relative to set of control group maturities for the euro/$ pair, and up to 90 basis points wider for the yen/$ pair. These results are consistent dealers setting forward prices contemporaneously in response to public information.

Table 13: CIP and Order Flow, response of 1 week Deviations to quarter-ends, relative to control group of maturities >=1y

	(1)	(2)	(3)
	CIP_{euro}	CIP_{chf}	CIP_{yen}
Qend	-0.446***	0.536**	0.0946
	(0.104)	(0.243)	(0.216)
post2015	-19.39***	-11.67***	-9.954***
	(2.311)	(2.346)	(3.335)
Qend $\times$2015	0.881***	0.408	2.100***
	(0.151)	(0.288)	(0.365)
Qend $\times \mathbb{1}[1w]$	-9.325***	-7.940***	-13.28***
	(0.138)	(0.263)	(0.195)
post2015 $\times \mathbb{1}[1w]$	3.631***	-4.360**	0.936
	(1.001)	(1.705)	(3.619)
Qend $\times post2015 \times \mathbb{1}[1w]$	-39.06***	-59.09***	-97.04***
	(0.147)	(0.305)	(0.446)
Constant	-9.395	-35.91***	-1.904
	(9.891)	(5.300)	(20.43)
Observations	10,866	10,785	10,874
Number of pair_tenor	8	8	8
Controls	Yes	Yes	Yes
Post2008	Yes	Yes	Yes

Note: This table regresses CIP deviations and order flow for 1 week euro/$, chf/$ and yen/$ FX swaps relative to a set of long term maturities, against a post2015 dummy and an interaction of quarter-ends with the post 2015 dummy and the treatment maturity (1 week) $Qend \times post2015 \times \mathbb{1}[1w]$. $Qend$ is a dummy indicating the week prior to quarter-ends, and tests for the effect of bank regulations tightening leverage on CIP deviations. Standardized order flow OF is measuring the net buyer transactions of swapping euros, chf and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week swaps. 1 Week CIP deviation is calculated using TR tick history quotes on 1 week forward rates. For longer-term swaps, we use CIP deviations for the 1Y,2Y,3Y,5Y,7Y and 10Y cross-currency swaps obtained from Bloomberg Swap Repository. Controls include the USD libor-ois spread, the VIX index, and the USD Trade weighted exchange rate. Sample period is from 01/13-12/17, and data is daily. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.