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

Olav Syrstad and Ganesh Viswanath-Natraj*

This Draft: April 30, 2021

Abstract

This paper investigates price discovery in foreign exchange (FX) swaps. Using data on inter-dealer transactions, we find a 1 standard deviation increase in order flow (i.e. net pressure to obtain USD through FX swaps) increases the cost of dollar funding by up to 4 basis points after the 2008 crisis. This is explained by increased dispersion in dollar funding costs and quarter-end periods. We find central bank swap lines reduced the order flow to obtain USD through FX swaps, subsequently affecting the forward rate. In contrast, during quarter-ends and monetary announcements we observe high frequency adjustment of the forward rate.

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

JEL Classifications: E43, F31, G15

*Norges Bank (Olav.Syrstad@Norges-Bank.no) and Warwick Business School (ganesh.viswanath-natraj@wbs.ac.uk) respectively. This working paper should not be reported as representing the views of Norges Bank . The views expressed are those of the author and do not necessarily reflect those of Norges Bank. We would like to thank Saleem Bahaj, Barry Eichengreen, Gerardo Ferrara, Yuriy Gorodnichenko, Pierre-Olivier Gourinchas, Ingomar Krohn, Richard Lyons, Dagfinn Rime, Andrew Rose, Andreas Schrimpf, Kjetil Stiansen, Ingebjørg Hansen Sævareid, 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.

1 Introduction

Foreign Exchange (FX) swaps allow market participants to hedge exchange rate risk arising from currency mismatch between assets and liabilities. After growing steadily over the past decade, FX swaps are now the most traded foreign exchange instrument worldwide, with a daily turnover of approximately $3.2 Trillion USD (2019 BIS triennial survey). In theory, the pricing of FX swaps is pinned down by Covered Interest Parity (CIP) - a renowned no-arbitrage relationship in international finance. CIP states that the rate of return on equivalent domestic and foreign assets should equalize after covering exchange rate fluctuations in the FX swap market. However, the FX swap market has been subject to considerable scrutiny since the global financial crisis, as the pricing no longer obeys the iron law of CIP. Since 2008, CIP deviations have been large and persistent, and have implied a systematic premium to swap EUR, CHF and JPY into USD via FX swaps (Figure 1). In this paper we focus on the mechanisms that govern price-setting in the FX swap market.

While much of the recent literature focuses on why CIP deviations exist, and range from explanations that center on limits to the supply of dollars in the FX swap market due to bank regulations (Du et al., 2018; Cenedese et al., 2019; Bräuning and Puria, 2017) and funding constraints (Rime et al., 2017; Liao, 2020), as well as factors that lead to an excess demand for dollars in the FX swap market (Borio et al., 2016; Sushko et al., 2017), less is understood about the role of price-setting in the FX swap market. This paper aims to fill this gap. To this end, we examine order flow - the net of buyer and seller initiated transactions - as a fundamental signal used by dealers to update the forward rate of the FX swap contract. In particular, we investigate the price impact of order flow before and after the financial crisis and how dealers respond to different types of information.

When a no-arbitrage relationship like CIP holds tightly, the role of order flow is confined to correcting short-lived periods of mispricing. In the pre-crisis period, money markets were characterized by low heterogeneity in funding costs where Libor (London interbank offered rate) acted as an accurate representation of banks' marginal cost across currencies. This made price-setting in the FX swap market a straightforward process, where the dealer takes interest rates in respective currencies as given. The dealer then sets the forward rate according to CIP so that the returns are equalized after covering the exchange rate risk. Hence, we hypothesize that the price impact of order flow is small prior to 2008. In contrast, the post-crisis period is characterized by a large dispersion in funding costs, differences in funding availability across currency areas and tighter constraints on banks' balance sheets. This makes it difficult for dealers to determine the equilibrium price. We hypothesize that dealers use order flow in the post-crisis period as a signal to set the forward rate. By exploiting time variation in the dispersion of funding costs and balance sheet constraints we examine how these factors can account for an increase in the price impact of order flow.

Our order flow measure is based on transaction level data from the Thomson Reuters D2000-2 platform. This platform registers inter-dealer transactions in the FX swap market where each trade is signed as either a buyer or a seller initiated transaction. The daily net of buyer and seller initiated transactions constitutes our order flow measure. In our sign convention, we interpret a positive order flow as net buying pressure to obtain USD through FX swaps. Due to superior market depth, we use 1-week maturity as our preferred tenor and base our empirical analysis on the 1-week FX swap order flow and 1-week deviation from CIP.[1]

We start by developing a microstructural model of the FX swap market. The model has three key agents; customers, arbitrageurs and dealers. Customers are managing the currency exposure on their balance sheets, for example by swapping foreign currency into USD. Arbitrageurs provide funds through the FX swap market when arbitrage opportunities appear. Dealers act as intermediaries and match the flows of customers and arbitrageurs and typically try to keep their positions flat to avoid financing inventories (Lyons, 1995; Bjønnes and Rime, 2005). 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 the price-setting of FX swaps. We can use this framework to study how the price impact of order flow is governed by shocks to arbitrageurs. For example, the model predicts that a tightening of funding and balance sheet constraints leads to an inelastic supply of arbitrage capital, with dealers adjusting the price substantially to avoid order flow and balance inventories.

Guided by our model, we first estimate the price impact of order flow, and find it has increased substantially after the global financial crisis in 2008. Since the crisis, a positive 1 standard deviation shock to order flow, i.e. demand to borrow USD through the FX swap market, causes a widening of CIP deviations by up to 4 basis points. That is, when the demand for USD in the FX swap market increases, the cost of obtaining dollars through FX swaps increases as well. We then test why the price impact of order flow is a post-crisis phenomenon by examining potential differences in the price impact of order flow in periods when the heterogeneity in US funding costs is large and when balance sheet expansion is particularly costly for banks.[2] Our estimates reveal that up to three quarters of the increased price impact can be attributed to periods when funding heterogeneity in USD is high and when the FX swap contract crosses regulatory reporting dates at quarter-ends. Higher funding heterogeneity

[1] Note that our aim is not to precisely measure CIP arbitrage opportunities, but rather price-setting in the FX swap market. We are therefore using 1-week Libor rates as the benchmark rate in our CIP calculation. Importantly, by examining CIP deviations instead of the forward rate directly, we control for movements in the forward rate that relates to changes in the interest rate differential.

[2] We define periods of funding heterogeneity by the daily cross sectional dispersion in 3-month US Libor panel quotes.

reduces the number of potential arbitrageurs as an increasing share of market participants face funding costs exceeding the threshold necessary to reap arbitrage profit. Similarly, regulatory reporting at quarter-ends give arbitrageurs incentives to reduce their provision of arbitrage capital. Consequently, a larger price adjustment is necessary for dealers to balance inventories.

In addition to the time varying price impact of order flow, we also test whether news is impounded in the price contemporaneously, or through trading (see Evans and Lyons (2005) for analysis on the FX spot market). Our model predicts that *private* information is revealed through order flow meaning that prices adjust as a result of trading activity. For example, suppose in response to a shock to its access to dollar funding, a Euro area bank now obtains dollars via the FX swap market. If the bank's information is private and not known to the dealers before the order appears, these excess demands translate to order flow in the inter-dealer market, which can then be used by dealers to update the forward rate. Alternatively, we hypothesize *public* information is impounded in the price contemporaneously. For example, consider a scheduled monetary announcement of a central bank, where the outcomes of the meeting are conveyed to all market participants simultaneously. If the announcement implies a change in the interest rate differential between two currencies, the dealer can reset the forward rate to match the change in the interest differential. In this setting, the monetary news is impounded in the price, suggestive of efficient price-setting in the FX swap market.

We test whether the public or private information view is relevant in price-setting by studying three different types of events. First, we examine the effect of Federal Reserve Swap lines during the period 2007-2010. The swap lines allowed foreign central banks to provide US dollar funding directly to their own eligible counterparties. By doing so, a larger set of counterparties were able to access USD directly from the central bank rather than via the FX swap market.[3] Although it is publicly announced when these auctions take place, the dealers do not have detailed information on whether individual counterparties would draw on the swap line.[4] Therefore, we expect swap lines will reduce the demand for USD through FX swaps and lower the order flow into USD. Second, we look at dates when the FX swap contract crosses quarter-ends. A large number of banks report quarter-end balance sheet snapshots to regulators. This implies incentives to reduce the size of the balance sheet leading to a more inelastic supply of arbitrage capital and significant price effects over reporting dates, as documented in Du et al. (2018). Given quarter-ends are public information and known to dealers in advance, we

[3] 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.

[4] 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 are revealed as positive order flow.

hypothesize contemporaneous price adjustment. Third, we identify monetary policy surprises to test whether the adjustment in the forward rate following monetary policy announcements happens through order flow. Following our example of a monetary announcement constituting public information, our theory points towards monetary news being impounded in the forward rate contemporaneously.

Turning to the empirical evidence, we find evidence that the swap lines reduced the order flow into USD which in turn affected the forward rate, supporting the private information hypothesis. In response to quarter-ends, we utilize high frequency data of forward rates to show a large contemporaneous price adjustment exactly at the hour the FX swap contract crosses quarter-ends, with the full price adjustment priced within two hours. Finally, in line with the hypothesis of public information we find no effect on order flow of monetary policy announcements. These results highlight that dealers efficiently adjust the price according to publicly available information.

Roadmap. The paper is outlined as follows. Section 2 provides an overview of related literature. In section 3, we outline definitions of covered interest rate parity, FX swaps and order flow and describe the data. In section 4, 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 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 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, 2020; 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), costs to leverage such as shareholder risk (Andersen et al., 2019) and rising counterparty or liquidity risk (Baba and Packer, 2009; Mancini Griffoli and Ranaldo, 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 (Sushko et al., 2017; Bahaj et al., 2018; Ivashina et al., 2015; Iida et al., 2016). This paper contributes to understanding CIP violations by understanding how constraints on the 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 rate 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). 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 FX swaps. The first is that customers in the FX swap market are trading for hedging purposes. In contrast, investors in the FX spot market are composed 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. Second, we add arbitrageurs to the framework as they attempt to make systematic profits from the mispricing of the forward rate. Using our framework, we derive a price-setting relation in which price adjustment of the FX swap, which we denote by the change in the CIP deviation, is linearly related to order flow.

Finally, we relate to a recent interest in understanding the microstructure and impact of order flow in the FX swap market. Krohn and Sushko (2017) examine how the market structure of the FX swap market has led to a reduction in market liquidity and rising bid/ask spreads during quarter-end periods. Cenedese et al. (2019) and Rime et al. (2017) find evidence that order flow has price impact in the post-crisis period. We extend their work in several ways. First, our measure of order flow is based on each trade being marked as buyer or seller initiated within the data from the trading platform, not the Ready-Lee algorithm. This eliminates potential errors and enable us to sign each trade. Second, through a model framework, we derive the price impact of order flow on the FX swap market through an inter-dealer market that sets the forward rate to minimize inventory accumulation. Third, in contrast to the existing literature we provide an explanation on how price impact of order flow has changed after the financial crisis. Our model framework enables us to link two factors, increased dispersion in dollar funding costs, and the tightening of leverage constraints, that explain up to three quarters of increased price impact we observe empirically in the post-crisis period. Fourth, we find that the source of information matters: in response to public announcements, dealers set the forward rate 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.

3 Definitions and data

Definitions

Foreign exchange swaps

Foreign exchange swaps, also known as spot-forward contracts, are used by banks and corporates to hedge balance sheet risk. 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. [5] We illustrate the legs of a EUR/USD FX swap in Figure 2. In the first leg of the contract, the customer exchanges a principal of K EUR at the current spot rate S USD per EUR. The customer receives SK USD. 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 K EUR, and the dealer then receives FK USD, where F is the forward rate of the contract.

In the empirical analysis the focus is on short-term FX swaps with maturity of 1-week. We focus on this maturity because the majority of platform trading in FX swaps happens at short maturities. At longer maturities, the use of brokers and telephone-based trading are more common.

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 USD or EUR. The total cost of borrowing 1 USD directly is $1 + r^f_\$$. Alternatively, the investor can borrow USD via the FX swap market. To do so, they borrow $\frac{1}{S}$ EUR, where S is the quotation in USD per EUR. The total cost in EUR is then $\frac{1+r^f_d}{S}$. They exchange the EUR into USD and hedge the 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.

[5]Similarly, a corporate may hedge the currency mismatch of their cash flows, for example if a European corporate has profits in USD from their offshore activities, they will hedge the foreign exchange risk by swapping their USD receivables with EUR.

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

Since 2008, the cost of borrowing USD through the FX swap market - the synthetic interest rate in USD - based on EUR, CHF and JPY has been higher than the corresponding direct funding cost in USD. The CIP deviations can therefore be interpreted as a synthetic dollar borrowing premium. We document this in Figure 1, which plots 1 year CIP deviations for the EUR/USD, CHF/USD and JPY/USD pairs.

In this paper, when we refer to price-setting of the FX swap, we specifically refer to a dealer setting the forward rate, taking interest rates and the spot rate as inputs. 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 CIP arbitrage (Akram et al., 2008).

$$\Delta_{pre-crisis} \approx 0 \implies F = S\frac{1 + r_{\$}^{f}}{1 + r_{d}^{f}} \tag{2}$$

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 heterogeneity in funding spreads, leverage constraints and customer quality during this period. As we will outline in our microstructural model of the FX swap market, these factors can cause an inelastic supply of arbitrage capital, increasing the price impact of order flow.

Data

CIP deviations

To compute CIP deviations at the 1 week maturity, we use Thomson Reuters tick history which contains historical data on spot and 1 week forward rates of the EUR/USD, CHF/USD and JPY/USD pairs measure at 6 PM Central European Time. 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 3 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 EUR, CHF or JPY), S is the spot rate and F is the forward rate, calculated as the mid-point using bid and ask quotes.[6] A negative Δ indicates that synthetic dollar borrowing costs exceed local borrowing costs, and this is indeed the case for the EUR/USD, CHF/USD and JPY/USD 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.[7]

$$\Delta_t = 1 + i_{q,t} - \frac{F_t}{S_t}(1 + i_{b,t}) \tag{3}$$

Summary statistics for the three currency pairs are provided in Table 1, for the EUR/USD, CHF/USD and JPY/USD 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 the US Libor rate is less than a synthetic Libor rate based on borrowing in EUR, CHF or JPY and swapping into USD 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. CIP deviations exhibit considerable persistence. Running a simple AR(1) specification (no constant) on CIP deviation in the post 2008 sample, we find an estimate for the autoregressive coefficient of 0.58. This translates to a half-life of approximately 1.3 days. [8]

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 EUR, CHF or JPY into USD. Conversely, a transaction is seller initiated if the transaction is swapping USD into foreign currency. To measure order flow at short-term maturities, we use the Reuters D2000-2 trading platform, which contains inter-dealer trades from January 1st 2005 to September 1st 2017 in FX swaps for the EUR/USD, CHF/USD and JPY/USD pairs. We use the 1 Week maturity as it is the most liquid and traded pair at maturities above 1-day. 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. Additionally, our data set has a column indicating if the trade was buyer or seller initiated. Using this data, we can construct a measure of order flow. The measure of order flow is then given as the net of buyer initiated transactions, where buyer initiated transactions are signed

[6] To calculate the mid spot rate, we average the spot rates at ask and bid, $S = \frac{S_a + S_b}{2}$. Similarly, the forward rate is calculated as the mid point of bid and ask quotes, $F = \frac{F_a + F_b}{2}$

[7] We account for the exact number of trading days by properly adjusting for bank holidays in the respective currency pairs

[8] The half-life formula for an AR(1) process $CIP_t = \rho CIP_{t-1} + \epsilon_t$ is $\frac{log(0.5)}{log(\rho)}$.

+1 and seller initiated transactions are signed -1. 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. [9]

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

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 EUR/USD pair has the highest range of order flow, with a range of [-30,+30]. We provide plots of daily order flow in Figure 3. Given order flow reflects private information, and dealers aim to minimise the accumulation of order imbalances over time, we hypothesize weak persistence in order flow. We find little persistence in order flow with an AR(1) coefficient of 0.04, yielding a half-life of 0.2 days. This suggests the inter-dealer market price-sets at a high frequency to balance the market, supporting models of the FX market at the daily frequency (eg. Evans and Lyons (2002)).

Funding dispersion

We calculate the daily dispersion in the 3-month Libor contributions as a proxy for funding heterogeneity. The measure is computed as the difference between the highest and lowest daily submission by the contributing panel banks. A higher value indicates larger dispersion in funding costs among the panel banks. Data until February 1st 2014 for individual Libor submissions can be obtained from Bloomberg. After this date Intercontinental Exchange (ICE) took over as Libor administrator from British Bankers Association (BBA) and the data can be obtained from ICE. Figure 4 shows the dispersion in 3-month Libor during our sample period ranging from January 1st 2005 to September 1st 2017.

Bid/ask spreads and price volatility

In the empirical part of the paper we also exploit the high frequency data from the Thomson Reuters tick history to create bid/ask spreads and a measure of intra-day price volatility. The measure of bid/ask spreads is the daily average of the last observation each hour. Figure 5 shows the evolution of the bid/ask spreads during the sample period. As a measure of daily price volatility, we compute the daily standard deviation based on hourly observations. The intra-day price volatility is depicted in Figure 6.

[9] Note that the common way of measuring order flow is to follow the algorithm provided in Lee and Ready (1991), which sign transactions as buyer or seller initiated based on bid and ask quotes. In our data we know the direction of the trade (seller or buyer initiated) is already indicated. This means that we are able to sign all trades correctly.

4 Model

Before turning to the empirical results, we first develop a model to structure our testable hypotheses. As a starting point, we introduce 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. In addition to customers, there are a distinct group of arbitrageurs. The arbitrageurs can step in and supply funds in the FX swap market to earn arbitrage profits from mispricing of the forward rate in response to underlying demand from customer flows. The third group of agents are dealers, who set the forward rate of the FX swap. The objective of dealers is to match flows as much as possible, both from customers and 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.

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 factors that affect price impact. We identify two factors, shocks to arbitrageur capital in the form of heterogeneous funding costs and leverage constraints, increase the price impact of order flow.

Timing

The setup follows the timing for spot trading in Evans and Lyons (2002). Within a trading day there are 3 trading rounds. Rounds 1 and 3 are dealer-customer trading, and round 2 is inter-dealer trading. In rounds 1 and 3, dealers and customers trade. The dealer's objective is to match flows of swapping domestic currency into dollars with opposing flows. Dealers match flows between arbitrageurs that supply dollars and customers that demand dollars. Any unmatched flows are met by drawing on dealer inventory.

In round 2, each dealer that supplied dollars to customers from their inventory submits these excess demands in the inter-dealer market. The aggregation of dealer imbalances is equal to inter-dealer order flow, which measures the public's net demand for dollars at the spot leg of the FX swap. Figure 7 depicts the timing of customer-dealer and inter-dealer trades and price-setting,

Round 3 is when price-setting in the model occurs. Dealers reset the forward price so that the net supply of dollars by arbitrageurs absorb inter-dealer order imbalances from round 2. This is consistent with theories of market microstructure where dealers are sufficiently risk averse to holding inventory (see Lyons (1995) and Bjønnes and Rime (2005) for empirical evidence on dealers minimizing inventory). The framework for price-setting is similar in spirit to the portfolio shifts model in Evans and Lyons (2002), where the public absorb an excess demand for the currency in the third trading round through adjustment of the spot rate. We depart from this model in two fundamental ways. First, as we are examining price-setting in the forward market, we take the spot rate as given, with the dealer adjusting the forward rate in response to inter-dealer order flow. Second, the public absorption of inter-dealer order flow in the third trading round is occurring through arbitrageurs. Arbitrageurs absorb inter-dealer order flow through setting a forward premium that elicits sufficient arbitrage from borrowing in dollars and lending them in the FX swap market. In the portfolio shifts model, adjustment of the spot rate induces a change in speculator demands for the currency.

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 $x_{j,t}$ 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 CIP deviation, Δ_t, is the excess of the forward premium over the interest rate differential, $\Delta_t = f_t - s_t - (r^f_\$ - r^f_d)$.[10] In our model, the arbitrageur faces two limits to arbitrage: heterogeneous funding costs and leverage constraints. [11] We detail each of these channels below.

Funding costs

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). The dollar funding spread reflects individual arbitrageur funding margins over the risk-free rate.[12] We model this formally, with each arbitrageur j facing a marginal funding cost $\tilde{c}_{j,t}$ over the risk-free rate $r^f_\$$. We assume the funding cost is stochastic over period t with distribution $\tilde{c}_{j,t} \sim N(c_{j,t}, \sigma^2)$.

[10] Note that the definition of the CIP deviation in the model is the negative of the CIP deviation 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.

[11] We exclude counterparty risk as the market practice of paying margin in FX swaps implies that moves in the underlying spot exchange rate are effectively collateralized by the counterparty.

[12] Note that we are using the Libor fixing as a proxy for the risk-free rate in the empirical part of the paper. This is strictly speaking not accurate, but our mission in this paper is to investigate the price-setting in FX swaps, not to precisely measure arbitrage opportunities.

Leverage constraints

As the ratio of debt to total assets increases with more arbitrage capital, so does the marginal cost of obtaining dollars. We capture costs to arbitrageur leverage by imposing a constraint $\frac{x}{W} \leq \gamma$. 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, for example during quarter-end periods when leverage constraints prevent agents from borrowing dollars for arbitrage capital (Bräuning and Puria, 2017; Du et al., 2018; Cenedese et al., 2019). 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.

$$W_{t+1} = \underbrace{W_t(1 + r^f_{\$})}_{\text{return on wealth}} + \underbrace{x_{j,t}\Delta_t}_{\text{cip arbitrage}} - \underbrace{x_{j,t}\tilde{c}_{j,t}}_{\text{funding spreads}} \tag{4}$$

Drawing on the properties of the exponential distribution, maximizing the log of expected utility is equivalent to mean-variance preferences over wealth.

$$\max_{x^*_{j,t}} \rho \left(W_t(1 + r^f_{\$}) + x_{j,t}\Delta_t - x_{j,t}\tilde{c}_{j,t} \right) \tag{5}$$

Subject to

$$x^*_{j,t} \leq \gamma W_t \tag{6}$$

The equation for the supply of dollars by the arbitrageur takes the following piece-wise functional form, provided in equation 7. The optimal supply of dollars by an arbitrageur is given by $x_{j,t}$. λ_j is the Lagrangian on the leverage constraint. If the leverage constraint binds, the supply of dollars in the FX swap market is capped at γW. In the unconstrained region, arbitrageur supply is linearly related to the forward premium, and CIP deviation Δ.

$$x^*_{j,t} = \begin{cases} \frac{\Delta_t - c_{j,t}}{\rho\sigma^2} & , \lambda_j = 0 \\ \gamma W_t & , \lambda_j \neq 0 \end{cases} \tag{7}$$

To summarize, arbitrageur supply of dollars is positively related to the forward premium (and CIP deviation Δ), and negatively related to dollar funding spreads and leverage constraints.

Customers

Customers, typically banks, use the FX swap market to hedge their currency balance sheet mismatch. 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 CIP deviation Δ. Importantly, x_t^D is a measure of the net demand for USD at the spot leg of the FX swap.

$$x_t^D = \int_0^1 f(\theta_b, \Delta_t) db \tag{8}$$

The first determinant of net demand for USD in the FX swap market is θ_b, which measures counterparty quality. All else equal, counterparties 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 counterparty quality. The increase in counterparty risk is a key determinant 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 CIP deviation Δ. All else equal, a higher CIP deviation implies an increase in the net cost of swapping euros, swiss francs and yen into dollars. Evidence in Eguren Martin et al. (2018) suggests that in response to shocks to the CIP deviation, banks' net demand for dollars in the FX swap market declines.

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. Moreover, all dealers in FX swaps are associated with a bank. Therefore, the dealer faces the same funding costs and constraints as the mother bank that indeed can be part of the group of arbitrageurs. We denote the net dollar demands by customers to dealer j by x_j^D. Denote the net supply of dollars by arbitrageurs to dealer j by $x_{j,t}^*$. Unmatched flows in dollars are submitted to the inter-dealer market. Dealer-customer trading in the first round, where $\int_0^1 f_{t,1}^j(\theta_b, \Delta_{t,1}) db$ is the customer demand for dollars in FX swaps that is met by arbitrageur j, $x_{j,t,1}^*$ is the amount of arbitrage undertaken by arbitrageur j and dealer supply D_j is equal to the difference between customer demands and arbitrageur supply of dollars in FX swaps.[13]

[13]While we separate dealers and arbitrageurs, for ease of notation we will assume each arbitrageur is matched to a dealer. Therefore, when a customer demands dollars in the FX swap market, their demands are matched by an arbitrageur j and a dealer j, where $j = 1, 2, ..., N$.

$$\int_0^1 f^j_{t,1}(\theta_b, \Delta_{t,1})db = x^*_{j,t,1} + D_j \tag{9}$$

In round 2, a dealer that needs to maintain their inventory by demanding D_j dollars in the inter-dealer market. There are N dealers, and aggregation of dealer demands across the N dealers results in inter-dealer order flow. This is observable and measures the net demand for dollars by customers at the spot leg of FX swaps. Aggregating across all dealers, we obtain an expression for inter-dealer order flow OF_t, in equation 10. Inter-dealer order flow is equal to the net buying pressure of swapping EUR, CHF or JPY (domestic currency) into USD.

$$\begin{aligned} OF_{t,2} &= \sum_{j=1}^{N} D_j \\ &= \int_0^1 f_{t,1}(\theta_b, \Delta_{t,1})db - \sum_{j=1}^{N} x^*_{j,t,1} \end{aligned} \tag{10}$$

Figure 8 illustrates the structure of the dealer-customer and inter-dealer market, with an example of two dealers. Each customer has a net demand for dollar funding in the FX swap market. 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. Each dealer's excess demand for dollars is labeled as D_1 and D_2 respectively. Aggregating dealer demands 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. This can be used by dealers to update the forward rate of the swap, which leads us to our price-setting condition.

Definition [Price setting]: *The inter-dealer market sets a forward rate in round 3 to absorb dealer imbalances observed in the inter-dealer market in round 2.*

$$\sum_{j=1}^{N} x^*_{j,t,3} = \int_0^1 f_{t,3}(\theta_b, \Delta_{t,3})db + OF_{t,2} \tag{11}$$

In round 3, the inter-dealer market resets the price of the forward $f_{t,3}$ to absorb inter-dealer order flow in round 2.[14] This condition is necessary for inventory control; resetting the forward price creates sufficient arbitrage to absorb dealer imbalances (Lyons, 1995; Bjønnes and Rime,

[14]The setting of a forward rate is equivalent to setting the CIP deviation in our model, where $\Delta_{t,3} = f_{t,3} - s_t - (r^f_{\$} - r^f_d)$. The assumption behind price-setting is that the spot rate and risk-free rates in both currencies are kept constant. The dealer sets the forward rate. The forward premium then determines the amount of arbitrage profits made by an arbitrageur, and the cost of borrowing dollars in the FX swap market for customers.

2005). The price-setting condition is implicitly assuming an inter-dealer market that sets a common price for all dealers. This is a reasonable assumption, as if dealers set different prices, this would not be a sustainable equilibrium as other dealers will only execute swap trades with the dealer that sets the most favorable rate.[15] Intuitively, the price-setting condition is consistent with a market clearing condition, in which customer demands for dollars are equal to arbitrage supply of dollars in the FX swap market across the dealer-customer trading rounds (1 and 3).

$$\sum_{j=1}^{N} x^*_{j,t,1} + \sum_{j=1}^{N} x^*_{j,t,3} = \int_0^1 f_{t,1}(\theta_b, \Delta_{t,1})db + \int_0^1 f_{t,3}(\theta_b, \Delta_{t,3})db \tag{12}$$

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

Proposition 1: price impact of order flow

Assume the share of leverage constrained arbitrageurs is zero. Dealer price-setting uncovers a linear relation between order flow and the change in CIP deviations. The price impact of order flow is related positively to variance of funding costs and negatively related to the number of arbitrageurs N, $\beta = \frac{\rho\sigma^2}{N}$. *The intercept* $\alpha = \bar{c}_{j,t} - \bar{c}_{j,t-1} + \frac{\rho\sigma^2}{N}\left(\int_0^1 f_{t,3}(\theta_b, \Delta_{t,3})db - \int_0^1 f_{t-1,3}(\theta_b, \Delta_{t-1,3})db\right)$, *where* $\bar{c}_{j,t} = \sum_{j=1}^{N} \frac{c_{j,t}}{N}$.

$$\Delta_{t,3} - \Delta_{t-1,3} = \alpha + \beta OF_{t,2} \tag{13}$$

Proof: See appendix

Price-setting in the third trading round of the day is linearly related to inter-dealer order imbalances observed in the second round. We can expand on equation 13 and show that price-setting in the forward market is attributed to three components in equation 14.

$$\Delta_{t,3} - \Delta_{t-1,3} = \underbrace{\bar{c}_{j,t} - \bar{c}_{j,t-1}}_{\text{funding costs}} + \frac{\rho\sigma^2}{N}\left(\underbrace{\int_0^1 f_{t,3}(\theta_b, \Delta_{t,3})db - \int_0^1 f_{t-1,3}(\theta_b, \Delta_{t-1,3})db}_{\text{customer demand shocks}}\right) + \frac{\rho\sigma^2}{N}\underbrace{OF_{t,2}}_{\text{dealer imbalances}} \tag{14}$$

The first is adjustment in the funding costs for arbitrageurs. If funding costs increase from

[15] Moreover, inter-dealer trades are secured by daily margining practically eliminating potential differences in counterparty risk across dealers.

period $t-1$ to period t, arbitrageurs require compensation by demanding a higher forward premium in supplying dollars in the FX swap trade. The second component is the unanticipated change in customer demands. For example, these are due to liquidity shocks, or through a change in customer quality θ_b. A deterioration in customer quality (a downgrade of credit ratings) can affect the allocation of direct and synthetic dollar funding via the FX swap market. The third component is inter-dealer order flow observed in trading round 2. The price impact of order flow is increasing in the variance of funding costs, in the coefficient of absolute risk aversion and decreasing in the number of arbitrageurs. This is intuitive: limits to arbitrage mean the inter-dealer market needs to set the forward rate more aggressively to attract arbitrage capital to take the other side of customer trades. Through appropriate resetting of the forward rate, dealers are able to minimise inventory and match flows.

The heterogeneity of funding spreads is consistent with the empirical findings of Rime et al. (2017). Crucially, we argue that it is heterogeneity in dollar funding costs that matter when there is positive inter-dealer order flow, measured as a net demand for dollars in the inter-dealer market. If order flow is negative for the EUR/USD pair, then dealers will be net supplying euros, and it is instead the variance of euro funding costs that matter for the price impact of order flow. Two empirical tests naturally follow from our derived price impact parameter. First, the model predicts that periods of high dollar funding cost dispersion are periods of high price impact of order flow. Second, positive order flow (net demand for dollars in FX swap funding) have a higher price impact estimate than negative order flow.

Proposition 2: Binding leverage constraints

Suppose now that a fraction of arbitrageurs $\eta > 0$ of arbitrageurs are leverage constrained. Dealer price-setting uncovers a linear relation between order flow and the change in CIP deviations. The price impact of order flow is positively related to the share of leverage constrained arbitrageurs $\beta = \frac{\rho\sigma^2}{N(1-\eta)}$.
The intercept $\alpha = \bar{c}_{j,t} - \frac{1}{1-\eta}\bar{c}_{j,t-1} + \frac{\rho\sigma^2}{N}\left(\int_0^1 f_{t,3}(\theta_b, \Delta_{t,3})db - \frac{1}{1-\eta}\int_0^1 f_{t-1,3}(\theta_b, \Delta_{t-1,3})db\right)$, where $\bar{c}_{j,t} = \sum_{j=1}^{N} \frac{c_{j,t}}{N}$

$$\Delta_{t,3} - \frac{1}{1-\eta}\Delta_{t-1,3} = \alpha + \beta OF_{t,2} \tag{15}$$

Proof: See appendix

The second model prediction shows that when the leverage constraint is reached, a number of arbitrageurs have reached a maximum supply of dollars. A smaller number of arbitrageurs in round 3 need to supply dollars to match customer demands and offset order flow. This requires a higher price impact per unit of order flow to incentivise unconstrained arbitrageurs to supply the necessary dollars to absorb inter-dealer order imbalances. The prediction neatly maps to an empirical test of whether the price impact of order flow increases during quarter-ends. 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).

Proposition 3: Public vs Private Information Shocks

Consider a dealer information set Ω_t, which includes information on arbitrageur funding costs, leverage constraints and customer quality. Consider innovations to funding costs and customer quality that are outside dealer information sets.

$$c_{t,j} = \underbrace{E[c_{t,j}|\Omega_t]}_{\text{public information}} + \underbrace{\epsilon_{t,j}}_{\text{private information}}$$

$$\theta_{t,b} = \underbrace{E[\theta_{t,b}|\Omega_t]}_{\text{public information}} + \underbrace{\epsilon_{t,b}}_{\text{private information}}$$

Order flow is then equal to the innovations in customer demand and arbitrageur supply.

$$OF_{t,2} = \underbrace{\int_0^1 f(\theta_b, .) - \mathbb{E}\left[f(\theta_b, .)|\mathcal{I}_t\right] db}_{\text{customer type}} + \frac{1}{\rho\sigma^2}\sum_{j=1}^{N}\left(\underbrace{c_{j,t} - \mathbb{E}\left[c_{j,t}|\mathcal{I}_t\right]}_{\text{funding spreads}}\right) \tag{16}$$

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 16. 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. We provide examples of public and private information shocks in the context of the model.

Public information shocks: Examples include monetary announcements and quarter-end reporting requirements. A testable implication of our framework is that we expect to observe contemporaneous adjustment of the forward rate in response to public announcements.

Private information shocks: An example of a shock to bank quality that we test empirically is the introduction of central bank swap lines. 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.

To conclude, the model has provided a simple framework through which price-setting in the FX swap is mapped linearly to order flow. We test three predictions in our empirical evidence. First, based on proposition 1, we measure the price impact of order imbalances. We then test proposition 2; which states that heterogeneous dollar funding costs and leverage constraints during quarter-ends lead to increased price impact of order flow. In proposition 3, we test the public and private information views with an analysis of central bank swap lines, quarter-ends and monetary announcements.

5 Price Impact of Order Flow

Baseline specification

In this section, we examine the price impact of order flow. In proposition 1 of the model, we concluded that an increase in order flow in the inter-dealer market is consistent with excess demands for swapping other currencies into USD, i.e. borrowing USD through FX swaps. 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 the forward premium and a widening of CIP deviations. Our baseline specification for testing the price impact of order flow is outlined in equation 17.

$$\Delta CIP_t = \alpha + \beta_1 OF_t + \beta_j x_{j,t} + \epsilon_t \tag{17}$$

The outcome variable is the daily change in 1-week CIP deviations, where negative values indicate that it is more costly to obtain USD through FX swaps relative to the direct borrowing rate in USD. Our variable of interest, β_1, measures the price impact of order flow (OF). X is a vector of control variables including the change in the U.S. Libor-OIS spreads for 1-week and 3-month maturities, the VIX index, and the USD Trade weighted exchange rate. We run the specification for all currency pairs as a panel and for the EUR/USD, CHF/USD and JPY/USD pairs separately, and divide our sample into two periods, a pre 2008 period (January 2005 to December 2007), and a post 2008 period (January 2008 to September 2017).

By dividing our sample into before and after 2008 we are able to uncover potential changes in the price impact of order flow after the global financial crisis. Our justification is that during the pre 2008 period, CIP held tightly, indicating an elastic supply of arbitrage capital. Order flow is not expected to have any significant price impact, as there are relatively short-lived periods of mispricing in the FX swap market (Akram et al., 2008). However, in the post-crisis period, arbitrage capital becomes scarce. We hypothesize that dealers adjust prices more aggressively during this period to attract the necessary arbitrage capital and balance dealer inventories.

Our results are presented in Table 3. In columns (1) through to (4), we test for price impact in the pre-crisis period, and in columns (5) through to (8), we test for price impact in the post-crisis period. We find that order flow has significant price impact in the post 2008 period for all 3 pairs, with a one standard deviation change in order flow widening CIP violations by up to 4 basis points based on the panel specification in column (5). In contrast, there is no significance in the pre 2008 period.

Dynamic effects

In addition to the contemporaneous price impact of order flow, we test for dynamic effects using a structural vector autoregression (VAR) framework. Following the work of Hasbrouck (1991) and Ranaldo and Somogyi (2019), we estimate the following bivariate VAR of order flow OF and the first difference in CIP deviations ΔCIP, illustrated in equations 18 and 19. In equation 18, a contemporaneous shock to daily order flow is impounded in the price the same day, 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. The identification assumption is consistent with causality running from order flow to price-setting of the FX swap.

$$\Delta CIP_t = \alpha_1 + \sum_{k=1}^{L} \gamma_{1,k} \Delta CIP_{t-k} + \sum_{k=0}^{L} \beta_{1,k} OF_{t-k} + \epsilon_{1,t} \tag{18}$$

$$OF_t = \alpha_2 + \sum_{k=1}^{L} \gamma_{2,k} \Delta CIP_{t-k} + \sum_{k=1}^{L} \beta_{2,k} OF_{t-k} + \epsilon_{2,t} \tag{19}$$

Based on our specification with 7 lags, we test the effects of a 1 standard deviation shock to order flow on the CIP deviations in Figure 10. On the left panel, we test for effects during the pre 2008 period, and observe no systematic effect of order flow on the CIP deviation for all pairs of the EUR/USD, CHF/USD and JPY/USD. In the post 2008 period, we find the contemporaneous change in the CIP deviation is approximately 4 basis points, with insignificant price changes in the days following the shock.

Robustness test: rolling regressions show structural break in 2008

Further evidence for price impact variation over time is estimated using a method of rolling regressions. We plot the price impact coefficients of rolling regressions of order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. We use a series of controls based on the baseline specification (exchange rate, VIX, libor-ois spread) and quarter-end periods. A rolling window of 180 days is used in the baseline specification. We present the results in Figure 9. Consistent with our prior results, the price impact estimates show a structural break; with insignificant estimates in the pre 2008 period, that becomes persistently significant during the post 2008 period.

To explain the structural break in price impact of order flow, we note that the post 2008 period is characterised by increased dispersion in funding costs and tighter regulatory constraints. In pre-2008, the dealer set the forward rate based on a reference of risk-free rates and the spot rate. In a frictionless market, all participants use common benchmarks for the risk-free rate (typically Libor), yielding a single market clearing forward rate in equilibrium. In a market where CIP holds perfectly, order flow is less crucial as a price-setting factor. In contrast, the post 2008 period has led to a significant dispersion in funding costs has resulted in a segmented market (Figure 4). Dealers no longer have a common benchmark of the risk-free rate with which to calculate the equilibrium forward rate. There is no longer an equilibrium forward rate, leading dealers to use order flow as a signal for estimating underlying demand in the FX swap market. In addition, the fact that CIP held tightly in the pre 2008 period coincided with a period of increased liquidity in the forward market. Forward rates exhibited a lower level of volatility and lower bid-ask spreads (Figures 5 and 6). Higher liquidity in the inter-dealer market, as evident in lower bid-ask spreads and forward rate volatility, also contribute to the lower price impact during the pre-2008 period.

We now turn to two factors that can quantitatively explain the time variation in price impact. The two factors are an increase in funding cost heterogeneity and regulatory reporting during quarter-ends, that we hypothesize account for the increase in price impact observed in the post 2008 period.

Dispersion in funding costs and quarter-ends

Propositions 1 and 2 of the model in section 4 predicts that the price impact of order flow increases when heterogeneity in U.S. funding costs is large and when banks' balance sheet constraints are more binding. When funding cost dispersion increases in USD less market participants are in a position to conduct the arbitrage trade. The remaining arbitrageurs with favourable funding costs may face limits to the scalability of the arbitrage trade. Important reporting dates, such as quarter-ends, represent an opportunity to test how the price impact of order flow responds to tighter regulatory constraints. An increasing marginal cost of leverage suggests the supply of arbitrage capital becomes less elastic and the price impact of order flow increases.

To jointly test these hypotheses we run the following regression specification in equation 20. The variables $D_{FundingHet}$ and $Qend$ represent dummy variables for funding cost heterogeneity and quarter-ends, respectively. We are interested in the interaction between order flow and these variables to examine if the price impact of order flow changes when dispersion in funding costs increases and the FX swap contract crosses quarter-ends. The dummy variable $D_{FundingHet}$ captures days with high cross sectional dispersion among U.S. Libor panel banks in their individual submissions and when the 1-week FX swap contract matures after quarter-ends.[16] The dummy $Qend$ captures an increase in balance sheet constraints as regulatory authorities in most jurisdictions rely on quarter-end snapshot of banks' balance sheets. In addition to the control variables mentioned in the baseline specification, we also include the two dummies $D_{FundingHet}$ and $Qend$.

$$\Delta CIP_t = \alpha + \beta_1 OF_t + \beta_2 OF_t \times D_{FundingHet,t} + \beta_3 OF_t \times Qend_t + \beta_j x_{j,t} + \epsilon_t \tag{20}$$

Table 4 presents the results. Columns (1) to (4) measure the price impact of order flow during the pre-crisis period, and columns (5) to (8) measure price impact during the post period. Consistent with our theory, we find that the price impact of order flow is significantly higher during periods of high dispersion in Libor quotes in the post crisis period. The results suggest that larger heterogeneity in funding spreads implies that the forward rate has to adjust more aggressively to attract the necessary arbitrage capital to balance the market. Moreover, there is a substantial increase in price impact during quarter-end periods. This is also consistent with our theory of more inelastic supply of arbitrage capital when balance sheet constraints are more binding. Based on the panel regression estimates in column (5), days with high funding cost heterogeneity and quarter-end periods account for approximately three quarters of the increase in price impact after 2008.[17]

Robustness test: rolling regressions sorted on funding cost dispersion

Further evidence for price impact variation with bid-ask spreads and volatility is estimated using a method of rolling regressions sorted on the dispersion of LIBOR quotes. We outline the general steps of our procedure, with respect to a sorting variable Z_t.[18]

1. Create a dataset DS_t which includes the sorting variable Z_t, the daily change in CIP deviations ΔCIP_t, order flow OF_t and control variables X_t, which includes daily changes in the VIX, trade weighted exchange rate, and LIBOR-ois spreads. $DS_t = [Z_t, \Delta CIP_t, OF_t, X_t]$

[16] The dispersion dummy takes value 1 when the cross sectional dispersion (difference between the maximum and the minimum submitted quote) is within the highest quartile of the distribution on the respective day and zero otherwise

[17] To arrive at this calculation, we note that the aggregate price impact of a one standard deviation order flow shock is approximately 4 basis points. After controlling for funding heterogeneity and quarter-ends, the coefficient $\beta_1 \approx 1$, implying that three quarters of the price impact is explained by these two factors.

[18] The procedure is based on Payne (2003), which uses a VAR structure to study the impact of order flow on quote revisions in the spot foreign exchange market. In the paper, a VAR including order flow and spot quotes is sorted on variables that measure market liquidity (eg. trading volume). The procedure was then used to show how the price impact of trades change in low and high volume states.

2. Re-sort observations by $j = 1, 2, ..., N$, in ascending order of the sorting variable Z, $Z_1 < Z_2 < .... < Z_N$.

3. Re-sort observations of ΔCIP_t, OF and control variables according to $j = 1, 2, ..., N$. The new dataset DS_j is now sorted in ascending order of the sorting variable Z_j.

4. Run order flow specification $\Delta CIP_j = \alpha + \beta OF_j + X_j + \epsilon_j$, with a rolling window of 180 periods ($[k, k + 180]$, where $k = 1, 2, ..., N - 180$)

Using a dataset sorted on the dispersion in Libor quotes, we plot the price impact coefficients of rolling regressions of order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. We use a series of controls based on the baseline specification (exchange rate, VIX, libor-ois spread) and quarter-end periods. A rolling window of 180 days is used in the baseline specification. We present the results in Figure 11. Consistent with our theory of increased price impact due to constraints in dollar funding to arbitrage trades, the price impact estimates change continuously from periods of small to large dispersion in funding costs.

Direction of order flow

Following Rime et al. (2017), we now test for asymmetric price impact of order flow. We expect that the price impact of order flow when it is positive, i.e. there is net pressure for swapping domestic currency into USD in the inter-dealer market. This is because high funding cost heterogeneity in USD leads to a shortage of arbitrage capital in USD. However, for negative shocks to order flow, the availability of arbitrage capital in other currencies is what matters for price impact.

We present our results in Table 5. Columns (1) through to (4) depict the results from regressing positive and negative order flow on changes in CIP deviations and these two variables interacted with a dummy that takes the value of 1 after 2008, and zero otherwise. As expected, neither positive nor negative order flow have any price impact prior to 2008. After 2008, both negative and positive order flow is highly significant across all currencies. This result serves as an indication that insufficient arbitrage capital in USD as an important constraint after 2008.

In addition, we run a similar regression as specified in equation 20 on the panel of currencies, but now with the order flow split between positive and negative order flow. Columns (5) and (6) depict the pre and post 2008 results respectively. In the post 2008 sample, shown in column (6), the price impact of positive order flow is significantly larger than for negative order flow, and during periods when funding heterogeneity is high. This is consistent with our hypothesis that high funding cost heterogeneity in USD leads to a shortage of arbitrage capital in USD, making dealers more sensitive to positive order flow (net demand for swapping domestic currencies into

USD) in the FX swap market. During quarter-ends, we find both positive and negative order flow have large price impact. Dealers are aggressively adjusting the price to balance order flow independent of the direction. They are using the order flow as a signal to update the forward rate of the swap in periods when balance sheets are particularly constrained. The asymmetric impact of order flow supports the interpretation that funding strains and the corresponding heterogeneity in USD funding markets are the relevant factor in determining price-setting of the FX swap.

Bid/ask spreads and price volatility

To further substantiate the results on the price impact of order flow we examine bid/ask spreads and price volatility, calculated from high frequency quotes in the FX swap market. Bid/ask spreads are a proxy for market liquidity, and constructed as the daily intraday average of 1-week bid and ask for each currency pair. High bid/ask spreads can either indicate inventory risk for the dealer, or asymmetric information in the FX swap market. We calculate the daily standard deviation of price changes from high frequency intraday FX swap quotes as a proxy for price volatility.

We hypothesize that bid-ask spreads and intraday volatility increase during periods of funding heterogeneity and when the FX swap contract trades over quarter-ends. Tables 6 and 7 present results from regressing the bid/ask spread and price volatility on the quarter-end and funding heterogeneity variables used in specification 20. Columns (1) through to (3) test for effects in the pre-crisis period. Columns (4) to (9) test for effects in the post-crisis period, with additional dummies capturing the post 2015 period. First, the constant in the regression indicates that the bid/ask spreads are lowest for EUR/USD and highest for CHF/USD. This is in line with the interpretation that the EUR/USD is the most liquid currency pair while the CHF/USD is the least liquid. Similarly, price volatility increases during periods of large funding cost heterogeneity and during quarter-end periods. This is in line with order flow having stronger price impact and wider bid/ask spreads during these periods.

Most of the increase during quarter-ends have taken place after banks started to report leverage ratio to the public in 2015. In addition to lower market liquidity over quarter-ends, this may be related to leverage ratio increasing the costs of inventory for dealers. Wider bid/ask spreads act as a compensation for higher costs of being a dealer, and is consistent with empirical evidence in Krohn and Sushko (2017) which find bid/ask spreads rise during quarter-end periods.[19]

We now turn to whether the increased illiquidity in the inter-dealer market leads to an

[19] They make an additional point that market structure matters for dealer pricing. In particular, the role of smaller dealers providing arbitrage capital during quarter-ends leads to an increase in the observed bid/ask spreads

increase in price impact of order flow. We run a regression specification in equations 21 and 22. D_{spread} and D_{vol} are indicators for bid-ask spreads and volatility that take a value of one for values in the top 25 percentiles (upper quartile) over the post 2008 sample from January 1st 2008 to September 1st, 2017.[20]

$$\Delta CIP_t = \alpha + \beta_1 OF_t + \beta_2 OF_t \times D_{spread,t} + \beta_3 OF_t \times Qend_t + \beta_j x_{j,t} + \epsilon_t \tag{21}$$

$$\Delta CIP_t = \alpha + \beta_1 OF_t + \beta_2 OF_t \times D_{vol,t} + \beta_3 OF_t \times Qend_t + \beta_j x_{j,t} + \epsilon_t \tag{22}$$

In Table 8 we present the results of each specification. Columns (1) to (4) measure the price impact of order flow in periods of the 25 per cent of largest values of bid-ask spreads. Columns (5) to (9) measure the price impact of order flow in periods of the 25 per cent of largest values of forward rate volatility. Consistent with our theory, we find that the price impact of order flow is fully absorbed by periods of above median bid-ask spreads and intra-day forward volatility. This is evident in $\beta_1 \approx 0$, and the coefficient on order flow interacted with $D_{spreads}$ and D_{vol} being quantitatively significant, with a 1 standard deviation order flow widening CIP deviations by 5 to 6 basis points. The results suggest a deterioration in market liquidity, as indicated by widening bid-ask spreads and volatility, implies dealers are more sensitive to a change in inventories. The inter-dealer market sets the forward rate more aggressively to balance the market.

Rolling regressions sorted on bid-ask spreads and intra-day forward volatility

Further evidence for price impact variation with bid-ask spreads and volatility is estimated using a method of rolling regressions sorted on bid-ask spreads and volatility of the forward rate.[21] We plot the price impact coefficients of rolling regressions of order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. We use a series of controls based on the baseline specification (exchange rate, VIX, libor-ois spread) and quarter-end periods. A rolling window of 180 days is used in the baseline specification. We present the results in Figures 12 and 13. Consistent with our theory of increased price impact in an illiquid inter-dealer market, the price impact estimates change continuously from periods of small to large bid-ask spread, and from periods of low to high volatility of the forward rate.

[20] Similar results for our regression specification are obtained using the full sample of January 1st 2005 to September 1st, 2017.

[21] The procedure is based on Payne (2003), and is used in a preceding subsection to examine variation in price impact across periods of bid-ask spreads.

Central Bank Swap lines

Central bank swap lines provide incremental dollar liquidity to sufficiently dollar constrained banks. Banks with high dollar funding costs now have access to dollars via a central bank swap line. This will reduce their demand for dollar funding in the FX swap market. Swap lines may also provide an additional source of arbitrage capital, relaxing arbitrageur leverage constraints, with spillovers to relaxing inventory constraints in the inter-dealer market. We hypothesize that periods of swap line auctions result in a decrease in price impact due to an increased capacity of dealers to match customer transactions in the FX swap market.

$$\Delta CIP_t = \alpha + \beta_1 OF_t + \beta_2 OF_t \times D_{swapline,t} + \beta_3 OF_t \times Qend_t + \beta_j x_{j,t} + \epsilon_t \tag{23}$$

To test our hypothesis, we run a regression specification in equation 23. $D_{swapline}$ is an indicator that takes a value of one for days in which swap line auctions to the European Central Bank, Bank of Japan or Swiss National Bank occur, over the full sample from January 1st 2005 to September 1st, 2017.[22] The results are presented in Table 9. Consistent with our theory, we find that the price impact of order flow is attenuated during days of dollar liquidity provided by swap line auctions for the EUR/USD and JPY/USD pairs.[23] This is consistent with swap lines relaxing constraints to dollar funding and leverage constraints for arbitrageurs. The inter-dealer market sets the forward rate less aggressively to balance the market.

6 Public vs Private Information Shocks

In this section we empirically test the microstructural hypotheses of public and private information, outlined in proposition 3 of the model in section 4. We examine how price-setting in the FX swap market is determined in response to three different types of announcements, central bank swap lines, quarter-end reporting requirements and monetary policy surprises.

Central Bank Swap Lines

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, swap line auctions should be impounded in the price contemporaneously. In contrast, if the details of swap line auctions are private to dealers, price effects are due to the arrival of order flow.

We hypothesise that the swap lines constitute private information. While the date of swap line auctions are publicly known, the details of which banks have access to the swap line are unknown to dealers. Banks that have access to dollars via a central bank swap line will reduce

[22] We restrict the sample to swap line auction days that have a net positive allotment.

[23] The insignificant effect on CHF/USD is because swap lines were predominantly drawn by the European Central Bank and Bank of Japan.

their demand for dollar funding in the FX swap market. Therefore, dealers can update forward rates once they observe a decline in buyer initiated transactions. [24]

To test our hypothesis, we construct a global measure of total amounts outstanding for lines extended to the ECB, BOJ and SNB. Using data on Federal Reserve swap line allotments to counterparty banks during the period of 2008-2010, we compute the total stock of allotments as the total amount of all loans made by the Federal Reserve to counterparty central banks, less any loans that have matured. 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 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.

We test for the impact of the constructed measure of swap line allotment flows on the CIP deviations and order flow using the multivariate VAR framework is summarized in equations 24, 25 and 26. We use data on 1 week FX swaps as the majority of swap allotments are of a 1 week maturity. As well as the measure of CIP deviations CIP_t and order flow OF_t, we augment the bivariate VAR in section 5 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.

$$CIP_t = \alpha_1 + \sum_{k=1}^{L} \gamma_{1,k} CIP_{t-k} + \sum_{k=0}^{L} \beta_{1,k} OF_{t-k} + \sum_{k=0}^{L} \delta_{1,k} A_{t-k} + \epsilon_{1,t} \tag{24}$$

$$OF_t = \alpha_2 + \sum_{k=1}^{L} \gamma_{2,k} CIP_{t-k} + \sum_{k=1}^{L} \beta_{2,k} OF_{t-k} + \sum_{k=0}^{L} \delta_{2,k} A_{t-k} + \epsilon_{2,t} \tag{25}$$

$$A_t = \alpha_3 + \sum_{k=1}^{L} \gamma_{3,k} CIP_{t-k} + \sum_{k=1}^{L} \beta_{3,k} OF_{t-k} + \sum_{k=1}^{L} \delta_{3,k} A_{t-k} + \epsilon_{3,t} \tag{26}$$

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 14. Consistent with our hypothesis, there is a contemporaneous decline in order flow for the EUR/USD and JPY/USD

[24] 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 EUR/USD FX swap market. In either case, we predict an increase in allotments to reduce order flow.

pairs. The effect on order flow is strongest for the EUR/USD. 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 EUR/USD 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.[25] 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.

Direct effects on order flow

Adding to the dynamic effects of the swap lines on order flow and CIP, we run a simple regression where we regress order flow on a dummy for the days when the results of the swap line auctions are announced. As in our previous regressions we include the dummies for funding heterogeneity and quarter-ends. The control variables includes changes in Libor-OIS spreads (1w and 3m), VIX and broad USD index. The sample runs from January 1, 2007 to December 31, 2009, the period when the banks actively draw on the swap lines.

Table 10 depicts the results from the regression. In line with the VAR results, the order flow is substantially lower (less pressure to borrow USD in the FX swap market) on the days when the central banks announces the outcome of the USD auctions.

Quarter-end effects

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-ends can impact both customers and arbitrageurs in the FX swap market. First, quarter-ends limit capital to conduct CIP arbitrage trades, reducing the supply of dollars in the FX swap market. Second, there is evidence that a large increase in excess reserves of Euro area, Japan and Swiss banks during the post 2008 period increases the incentive to use FX swaps as an alternative source of dollar funding during quarter-ends. [26]

Quarter-end reporting obligations are known publicly to dealers, and in accordance with our microstructure hypothesis, we find evidence of contemporaneous price-setting. Figure 15 shows the reaction of the 1 week CIP deviation for the EUR/USD, CHF/USD and JPY/USD pairs

[25] In appendix **??** table **??** we find no effect of the swap lines on the price impact of order flow.

[26] This is due to FX swaps being *off balance sheet*, in contrast to short-term direct USD funding that increases leverage of the bank, see Rime et al. (2017) for more details

in September 2016. Once the quarter-end period ends, the forward rate contemporaneously adjusts back to its pre quarter-end level.

To shed more light on the speed of adjustment of the forward rate over quarter-ends we exploit high frequency tick data from Thomson Reuters Tick History. In Table 11 we consolidate the data to the last quote each hour and identify exactly the timing when the 1 week FX forward contract trades over quarter-end. For each currency pair we look at the 1 hour change in the FX swapped USD rate (the synthetic USD rate swapped from the respective currency 1-week Libor rate) from 5 hours before to 5 hours after the contract crosses quarter-ends. Finally, the data are averaged across all quarter-ends. The data show that the contemporaneous adjustment is strong across all currency pairs, in particular after 2015 when the Leverage ratio was introduced. A large part of the adjustment happens at exactly the hour when the contract first trades over quarter-end. However, for CHF and JPY there is further adjustment in the same direction up to 2 hours following the quarter-end. Moreover, for JPY, the currency where the central bank engaged in various forms of quantitative easing (and hence provided excess reserves to banking system), there is evidence of a large contemporaneous price adjustment over quarter-ends (14 basis points) even prior to the global financial crisis.

In addition to contemporaneous adjustment of the forward rate, we also test for effects on order flow. Given market participants face heterogeneous balance sheet constraints, the contemporaneous adjustment could be too large or too small. In theory, this means that a potential effect on order flow could be in both directions.[27] We test for systematic effects on order flow by simply regressing order flow on our dummy for dates when the 1-week FX swap contract crosses quarter-ends. Table 12 depicts the results.

We find that order flow increases (i.e. more flow into USD) during quarter-end periods for all currency pairs in the post 2008 sample, however for JPY the effect is not statistically significant. Furthermore, we do not find that the effect on order flow changes after the Leverage ratio was introduced in 2015. These results indicate that there is a tendency that the contemporaneous adjustment around quarter-end is not large enough to curb order imbalances. Interestingly, for JPY, where the contemporaneous price adjustment is largest, the effect on order flow is smallest.

Monetary Announcements

We argue in this section that as central bank announcements are public information, dealers respond by adjusting the forward rate contemporaneously. CIP deviations are decomposed into a forward premium and the interest rate differential. In response to a change in the risk-free

[27] For example, if dealers overshoot in their expectations of the tightness of leverage constraints, then this will result in a negative order flow. Conversely, if dealers underestimate the tightening of leverage constraints, this will result in positive order flow.

rate, we hypothesize that the forward premium reacts in a systematic way to offset the change in the interest rate differential. We illustrate this hypothesis in equation 27, 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.

$$\Delta = \underbrace{1 + r_{\$}^f}_{\text{direct}} - \underbrace{\frac{F \uparrow}{S}(1 + r_d^f \downarrow)}_{\text{synthetic}} \tag{27}$$

Figure 16 plots the forward premium of the EUR/USD, CHF/USD and JPY/USD in response to scheduled monetary announcements of the ECB, SNB and BOJ respectively. The ECB announcement we consider is the September 14th, 2014 announcement where the ECB lowered the deposit facility rate by 10 basis points.[28] 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/EUR exchange rate.[29] 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.[30] For each announcement, we observe a widening of the forward premium of approximately a similar magnitude to the surprise change in the interest rate, 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 test our hypothesis in equation 27 more concretely through an event study analysis of scheduled monetary announcements. For our measure of monetary surprises, we calculate the high frequency (30 minute window) 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 order flow on the surprise measure of interest rates. Our event study results in Table 13 show that monetary announcements have no statistical effect on order flow.[31] The results are consistent with contemporaneous adjustment of the forward premium as dealers offset changes to the interest rate differential.

---

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

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

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

[31] In line with this we find no effect of monetary announcements on the price impact of order flow, see table **??** in appendix **??**.

7 Conclusion

In this paper we detail a new channel for price discovery in FX swap markets. We identify order flow–the net of buyer and seller initiated transactions–as a fundamental signal used by dealers to update the price of the FX swap. Our key finding is that order flow has significant price impact in the post 2008 period, with no effects during the pre-2008 period. We explore two factors that restrict arbitrage capital: the increased heterogeneity of dollar funding costs and periods where the FX swap contract crosses quarter-ends, that account for the increase in price impact.

We first provide a model framework of the FX swap market. Agents supply dollars for CIP arbitrage, and demand dollars to hedge currency risk of their balance sheets. Dealers are the market-maker, and set a forward rate that equates customers net demand for dollars in the FX swap market with the supply of dollars of agents with arbitrage capital. We derive a price-setting rule in which dealers use order flow to update the forward rate of the swap.

We then test the framework empirically. Based on transaction level data for 1 week FX swaps in the inter-dealer market, we document a significant price impact of order flow in the post crisis-period, with a 1 standard deviation OF leading to a 4 basis point widening of CIP deviations. We estimate up to three quarters of the observed price impact is explained by an increase in the heterogeneity of dollar funding costs, and when the FX swap crosses quarter-end periods. Through the lens of the model, these factors lead to a reduction in arbitrage capital, and require dealers to increase the forward premium more aggressively to order flow and balance inventories.

Our second empirical contribution is to distinguish between public and private information in the FX swap market. We find evidence of contemporaneous price-setting during quarter-ends and monetary announcements. During quarter-ends, we document a high-frequency jump in the forward premium that corresponds to the hour during which the FX swap contract crosses quarter-ends. This suggests that dealers are pricing the effects of quarter-ends on arbitrage capital, consistent with public information. We also show gradual price adjustment through order flow in response to swap line allotments, consistent with dealers updating the forward rate in response to private information.

References

Akram, Q Farooq, Dagfinn Rime, and Lucio Sarno, "Arbitrage in the foreign exchange market: Turning on the microscope," *Journal of International Economics*, 2008, *76* (2), 237–253.

Andersen, Leif, Darrell Duffie, and Yang Song, "Funding value adjustments," *The Journal of Finance*, 2019, *74* (1), 145–192.

Avdjiev, Stefan, Wenxin Du, Catherine Koch, and Hyun Song Shin, "The dollar, bank leverage and the deviation from covered interest parity," 2016.

Baba, Naohiko and Frank Packer, "Interpreting deviations from covered interest parity during the financial market turmoil of 2007–08," *Journal of Banking & Finance*, 2009, *33* (11), 1953–1962.

Bahaj, Saleem, Ricardo Reis et al., "Central Bank Swap Lines," Bank of England Working Paper 2018.

Berger, David W, Alain P Chaboud, Sergey V Chernenko, Edward Howorka, and Jonathan H Wright, "Order flow and exchange rate dynamics in electronic brokerage system data," *Journal of international Economics*, 2008, *75* (1), 93–109.

Bjønnes, Geir Høidal and Dagfinn Rime, "Dealer behavior and trading systems in foreign exchange markets," *Journal of Financial Economics*, 2005, *75* (3), 571–605.

Borio, Claudio EV, Robert N McCauley, Patrick McGuire, and Vladyslav Sushko, "Covered interest parity lost: understanding the cross-currency basis," 2016.

Bräuning, Falk and Kovid Puria, "Uncovering covered interest parity: the role of bank regulation and monetary policy," 2017.

Cenedese, Gino, Pasquale Della Corte, and Tianyu Wang, "Currency mispricing and dealer balance sheets," *Available at SSRN 3327088*, 2019.

Du, Wenxin, Alexander Tepper, and Adrien Verdelhan, "Deviations from covered interest rate parity," *The Journal of Finance*, 2018, *73* (3), 915–957.

Evans, Martin DD and Richard K Lyons, "Order flow and exchange rate dynamics," *Journal of political economy*, 2002, *110* (1), 170–180.

_ and _ , "Do currency markets absorb news quickly?," *Journal of International Money and Finance*, 2005, *24* (2), 197–217.

_ **and** _ , "Understanding order flow," *International Journal of Finance & Economics*, 2006, *11* (1), 3–23.

Griffoli, T Mancini and A Ranaldo, "Deviations from Covered Interest Parity during the crisis: A story of funding liquidity constraint," Technical Report, Working Paper, Swiss National Bank 2009.

Hasbrouck, Joel, "Measuring the information content of stock trades," *The Journal of Finance*, 1991, *46* (1), 179–207.

Iida, Tomoyuki, Takeshi Kimura, Nao Sudo et al., "Regulatory reforms and the dollar funding of global banks: Evidence from the impact of monetary policy divergence," Technical Report, Bank of Japan 2016.

Ivashina, Victoria, David S Scharfstein, and Jeremy C Stein, "Dollar Funding and the Lending Behavior of Global Banks," *The Quarterly Journal of Economics*, 2015, *130* (3), 1241–1281.

Kozhan, Roman and Mark Salmon, "The information content of a limit order book: The case of an FX market," *Journal of Financial Markets*, 2012, *15* (1), 1–28.

Krohn, Ingomar and Vladyslav Sushko, "FX spot and swap market liquidity spillovers," *WBS Finance Group Research Paper*, 2017, (243).

Lee, Charles MC and Mark J Ready, "Inferring trade direction from intraday data," *The Journal of Finance*, 1991, *46* (2), 733–746.

Liao, Gordon Y, "Credit migration and covered interest rate parity," *Journal of Financial Economics*, 2020.

Lyons, Richard K, "Tests of microstructural hypotheses in the foreign exchange market," *Journal of Financial Economics*, 1995, *39* (2-3), 321–351.

Martin, Fernando Eguren, Matias Ossandon Busch, and Dennis Reinhardt, "Global banks and synthetic funding: the benefits of foreign relatives," 2018.

Payne, Richard, "Informed trade in spot foreign exchange markets: an empirical investigation," *Journal of International Economics*, 2003, *61* (2), 307–329.

Pinnington, James and Maral Shamloo, "Limits to arbitrage and deviations from covered interest rate parity," Technical Report, Bank of Canada staff discussion paper 2016.

Ranaldo, Angelo and Fabricius Somogyi, "Asymmetric Information Risk in FX Markets," 2019.

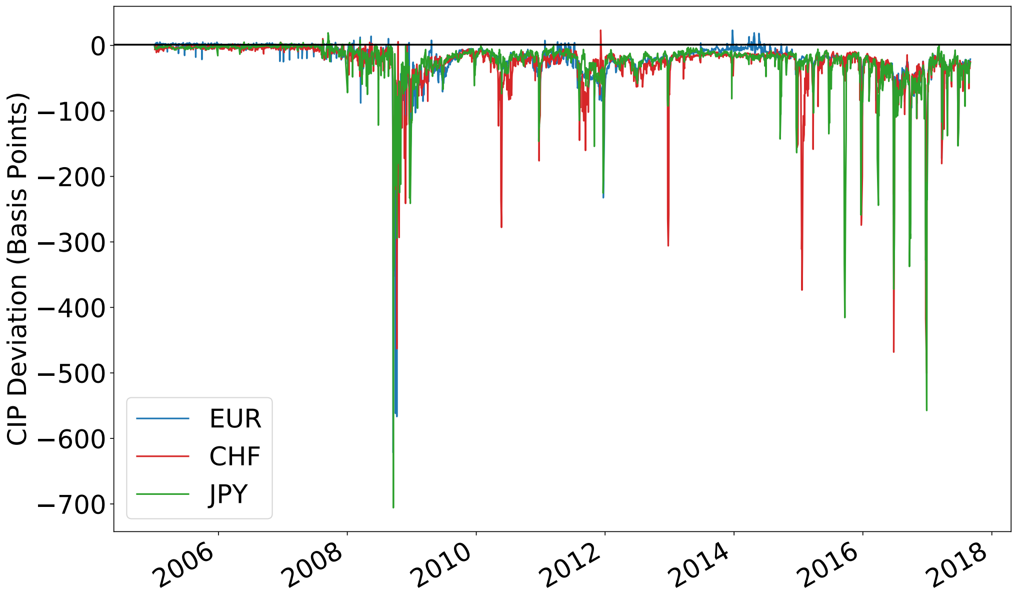
Rime, Dagfinn, Andreas Schrimpf, and Olav Syrstad, "Segmented money markets and covered interest parity arbitrage," 2017.

_ **, Lucio Sarno, and Elvira Sojli**, "Exchange rate forecasting, order flow and macroeconomic information," *Journal of International Economics*, 2010, *80* (1), 72–88.

Sushko, Vladyslav, Claudio EV Borio, Robert N McCauley, and Patrick McGuire, "The failure of covered interest parity: FX hedging demand and costly balance sheets," 2017.

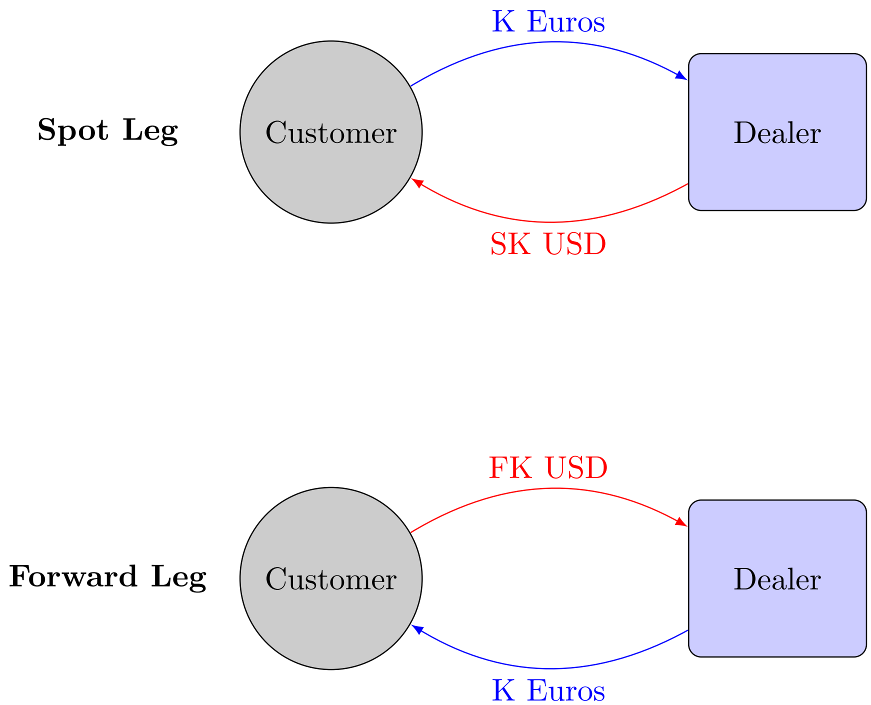
Figures

Figure 1: 1 Week CIP Deviations for EUR/USD, JPY/USD and CHF/USD pairs



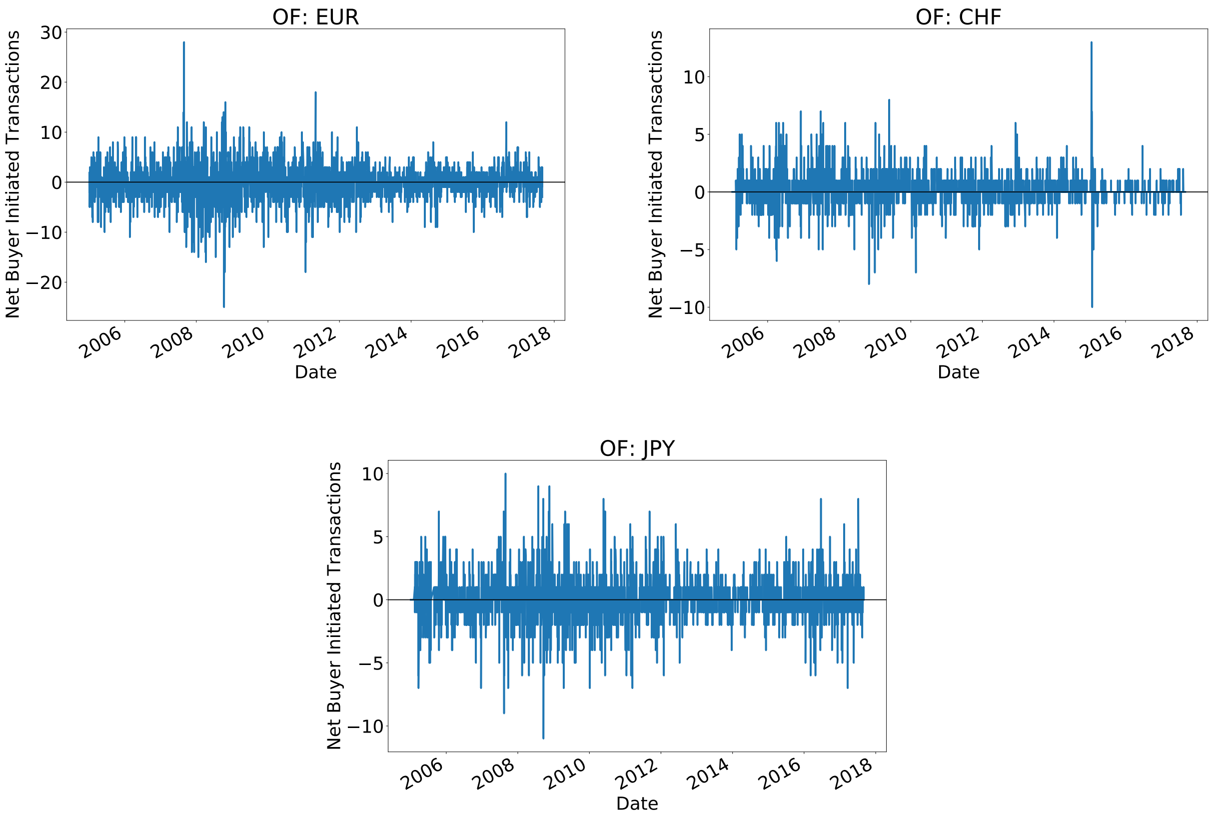
Note: This figure plots the 1 Week CIP deviation measured in basis points, obtained from Thomson Reuters Tick History. This provides a measure of CIP deviations based on a LIBOR benchmark rate. Negative deviations indicate a dollar borrowing premium for the EUR/USD, CHF/USD and JPY/USD pairs. Sample period is 01/2005-09/2017.

Figure 2: Foreign exchange swap



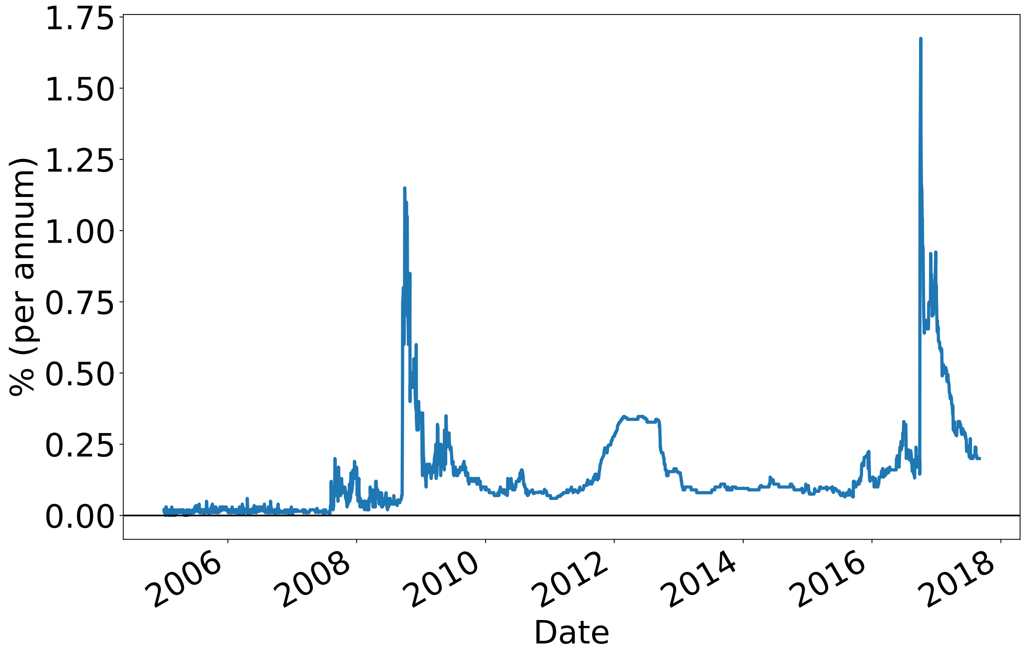
Note: FX swap is typically for maturities at less than 3m. At the spot leg, domestic currency and dollars are swapped at the prevailing spot rate. At maturity, the principals are then re-exchanged at the forward rate.

Figure 3: Daily Order Flow measure- EUR/USD, CHF/USD and JPY/USD



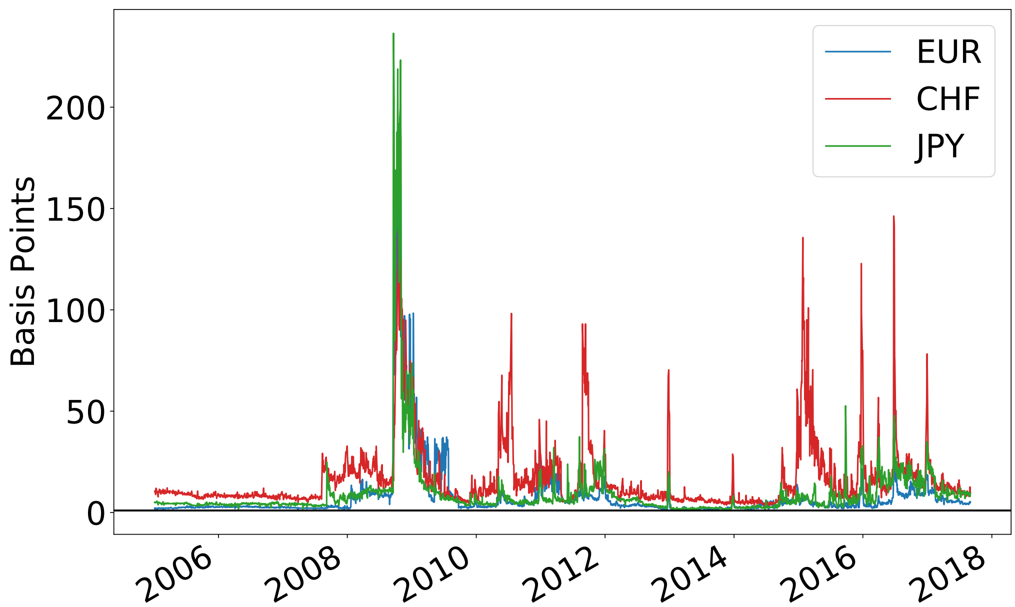
Note: Daily count order flow for EUR/USD, JPY/USD and CHF/USD pairs using the TR D2000-2, for FX swap maturities at 1 week. Order flow is given as the net of buyer initiated transactions, where buyer initiated transactions are signed $+1$ *and seller initiated transactions are signed* -1. $OF_t^{count} = \sum_{k=t_0}^{k=t} \mathbb{1}[T_k = B] - \mathbb{1}[T_k = S]$ *Sample period is 01/2005-09/2017.*

Figure 4: Range of Libor Fixing quotes



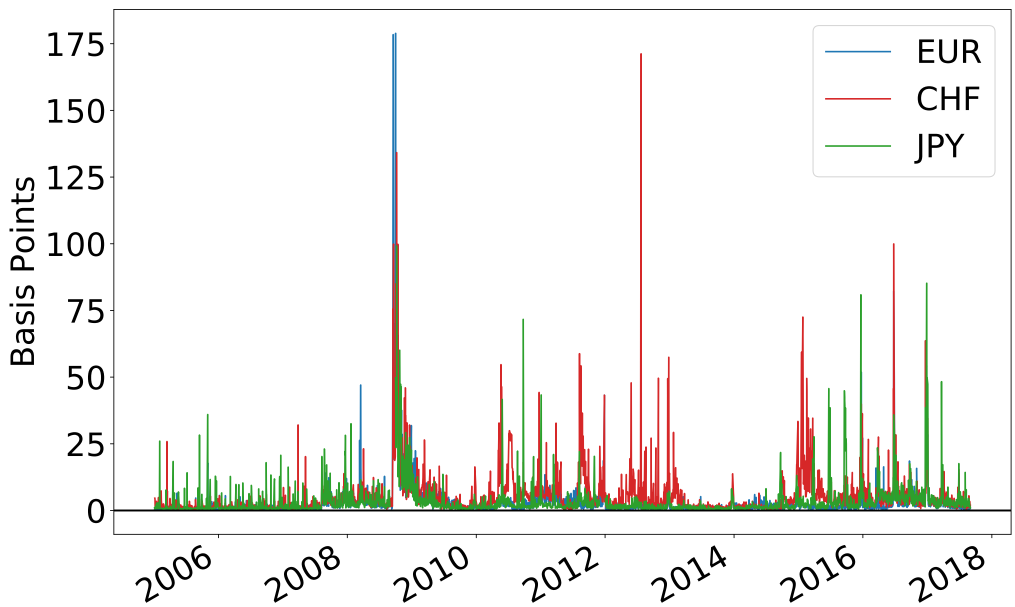
Note: The figure depicts the daily difference in percentage points between the highest and lowest submission among the contributing banks in USD Libor with 3-month maturity. The data are obtained from Bloomberg and Intercontinental Exchange (ICE). Sample period is 01/2005-09/2017.

Figure 5: Bid/ask spreads for EUR, CHF and JPY 1 Week FX swaps



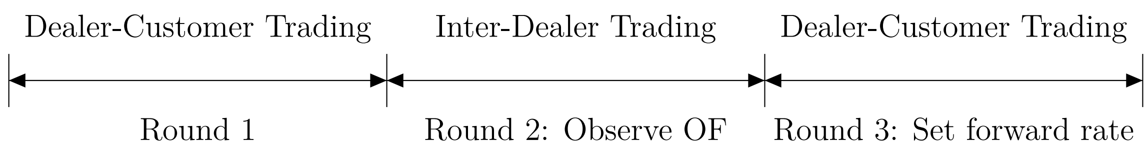
Note: The figure shows the daily average between the bid and the ask quotation based on hourly data from Thomson Reuters tick history. The bid/ask spread is expressed in basis points. Sample period is 01/2005-09/2017.

Figure 6: Intra-day forward rate volatility for EUR, CHF and JPY 1 Week FX swaps



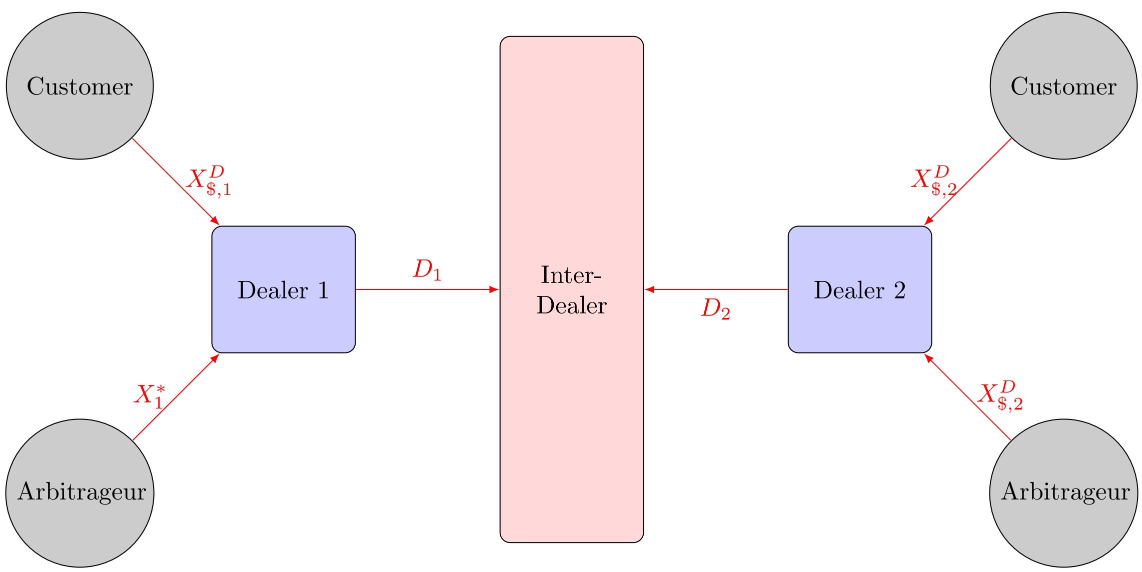
Note: The figure shows the daily standard deviation in swap points based on hourly data from Thomson Reuters tick history. The standard deviation is expressed in basis points. Sample period is 01/2005-09/2017.

Figure 7: Timing



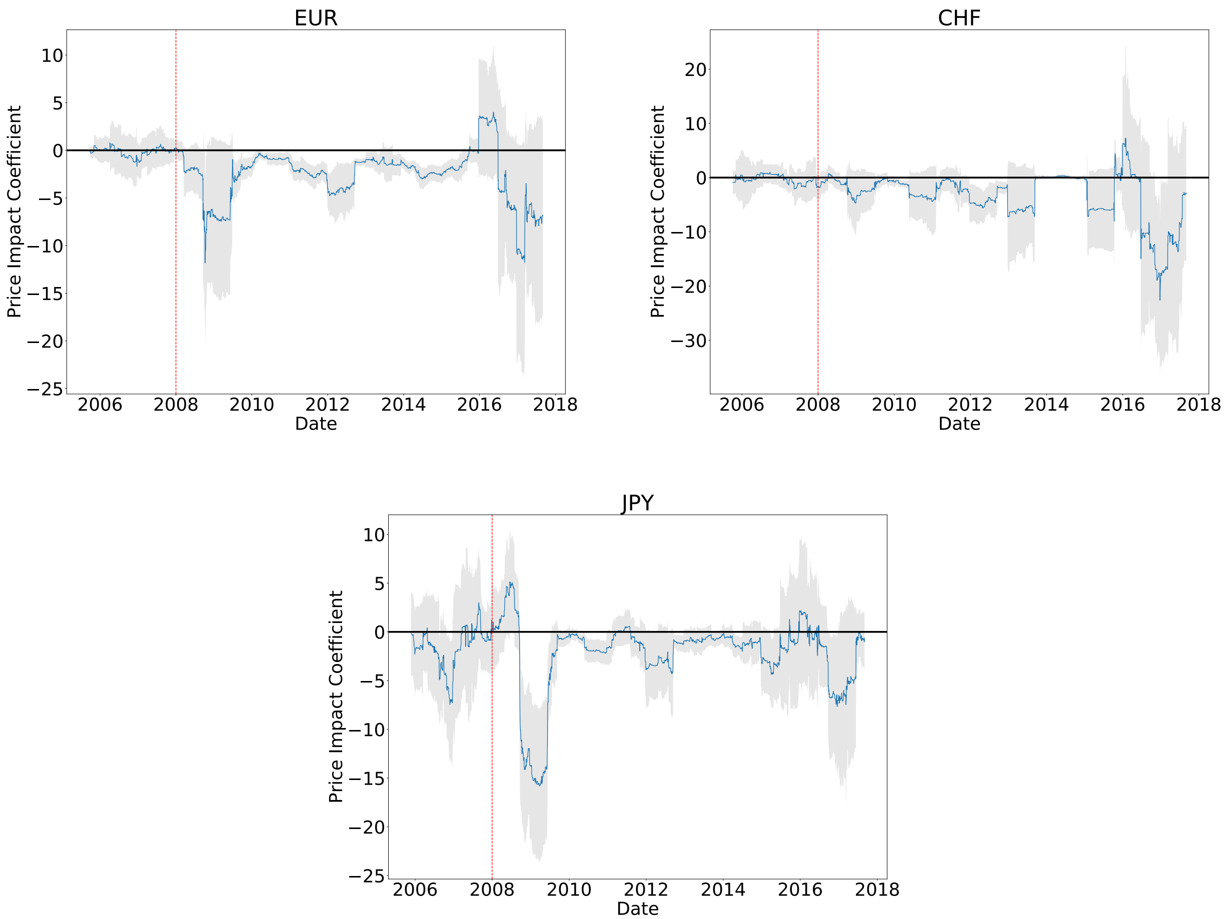
Note: This schematic illustrates the timing of the model. There are 3 rounds. Customer-dealer trading is executed in rounds 1 and 3. The inter-dealer market sets the forward rate in round 2. Aggregate dealer excess demands for swapping euros, swiss francs and yen into dollars in round 2 is observed as order flow. Dealers then use order flow observed in round 2 to set the forward rate in round 3.

Figure 8: Schematic of the interactions between customers, dealers and the inter-dealer market



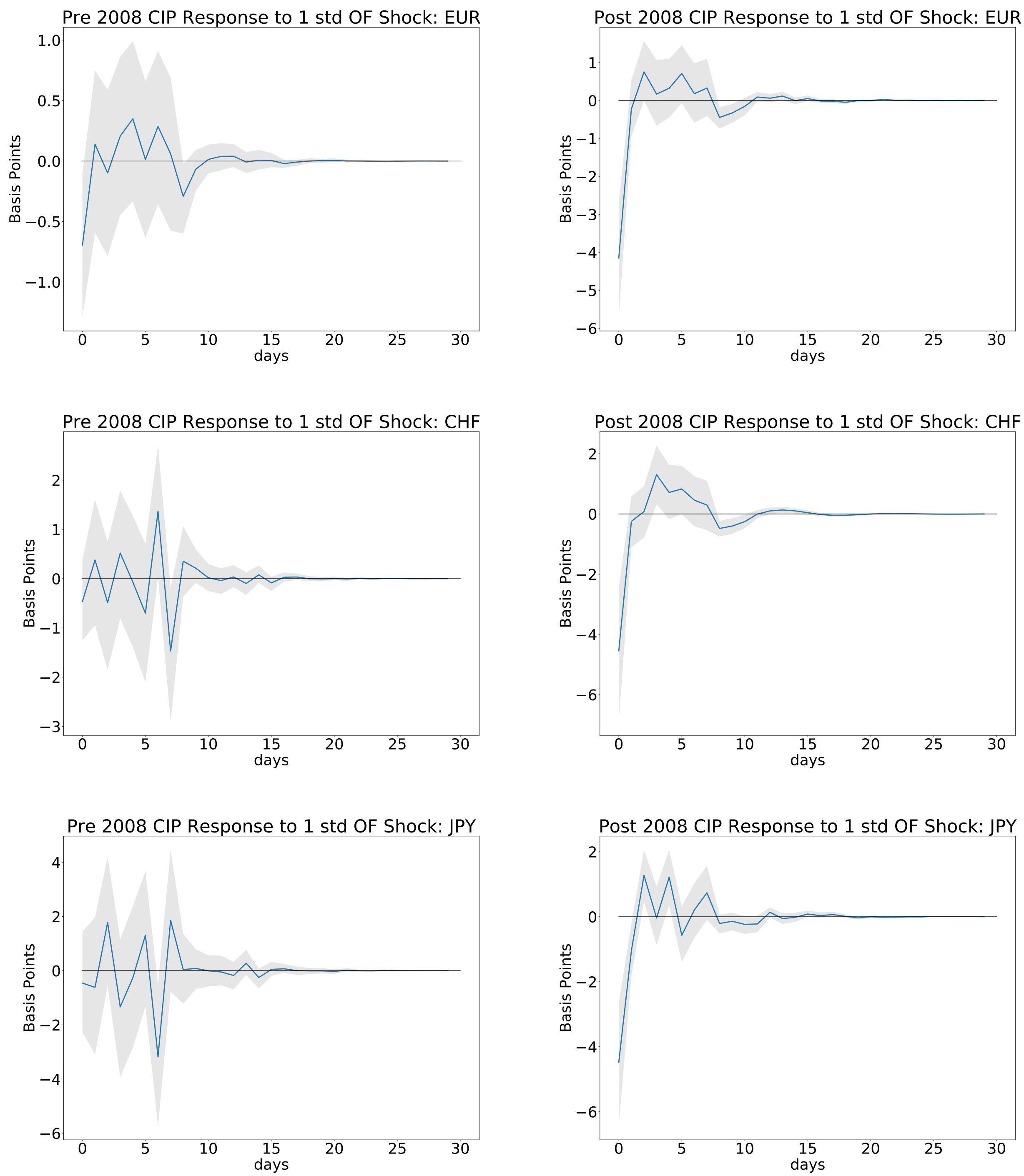
Note: This schematic illustrates the structure of the dealer-customer and inter-dealer market, with an example of two dealers. Each customer has a net demand for dollar funding in the FX swap market. The excess demands for dollar funding that cannot be met by the dealer's supply of dollars, is in turn submitted to the inter-dealer market. Each dealer's excess demand for dollars is labeled as D_1 and D_2 respectively. Aggregating dealer demands 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 9: Rolling regressions plot of price impact coefficients over time. Red dotted line indicates the post 2008 period.



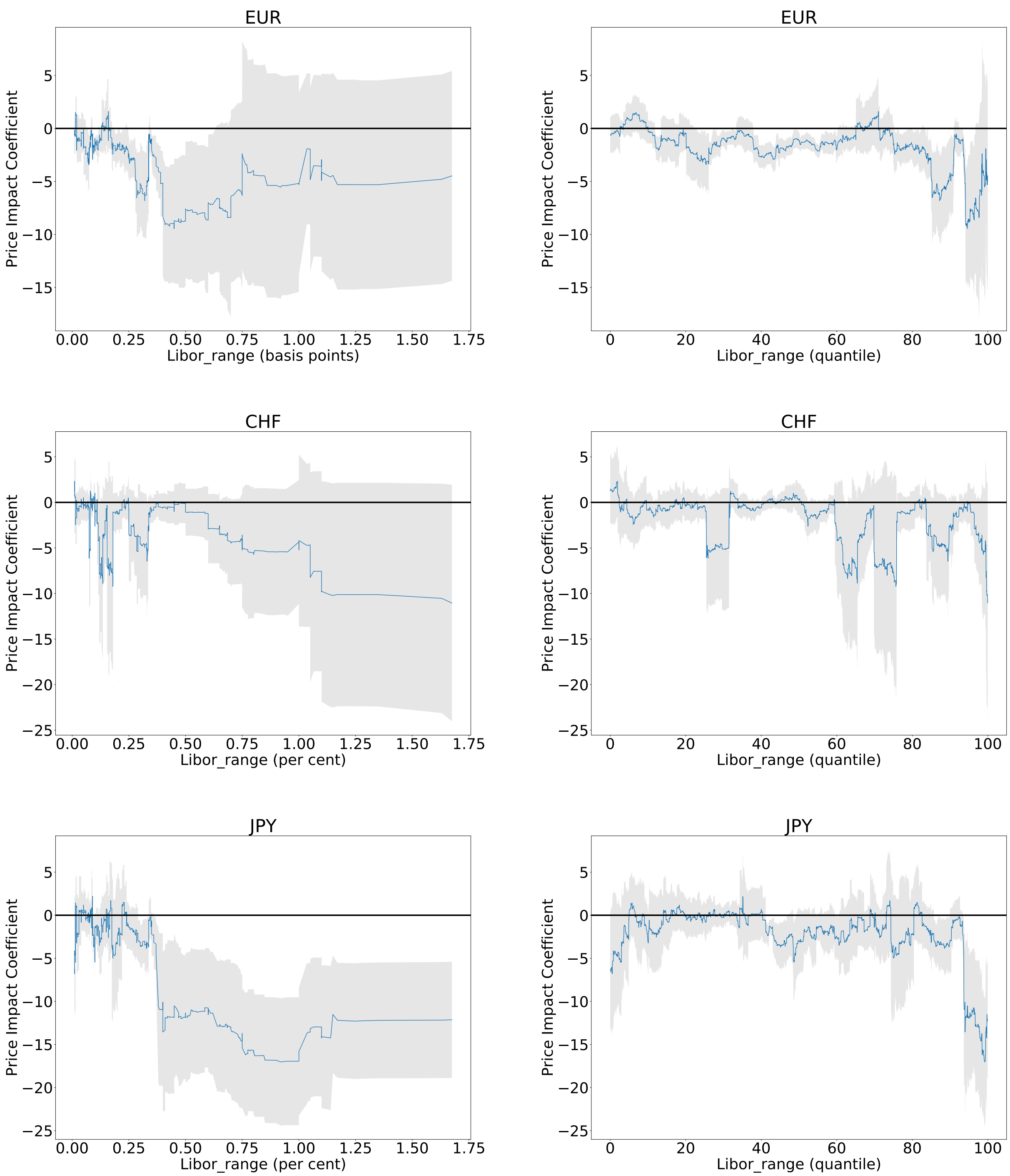
Note: This figure plots the price impact coefficients of rolling regressions of order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Rolling regressions are estimated using a window of 180 days. Red dotted line for January 1st, 2008 divides time periods into pre-2008 and post-2008. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate, and a dummy for periods when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Gray area denotes 95% confidence interval using White heteroscedasticity-robust standard errors.

Figure 10: Response of EUR/USD, JPY/USD and CHF/USD 1w CIP deviation to unit shock in count order flow in pre 2008 (left) and post 2008 (right)



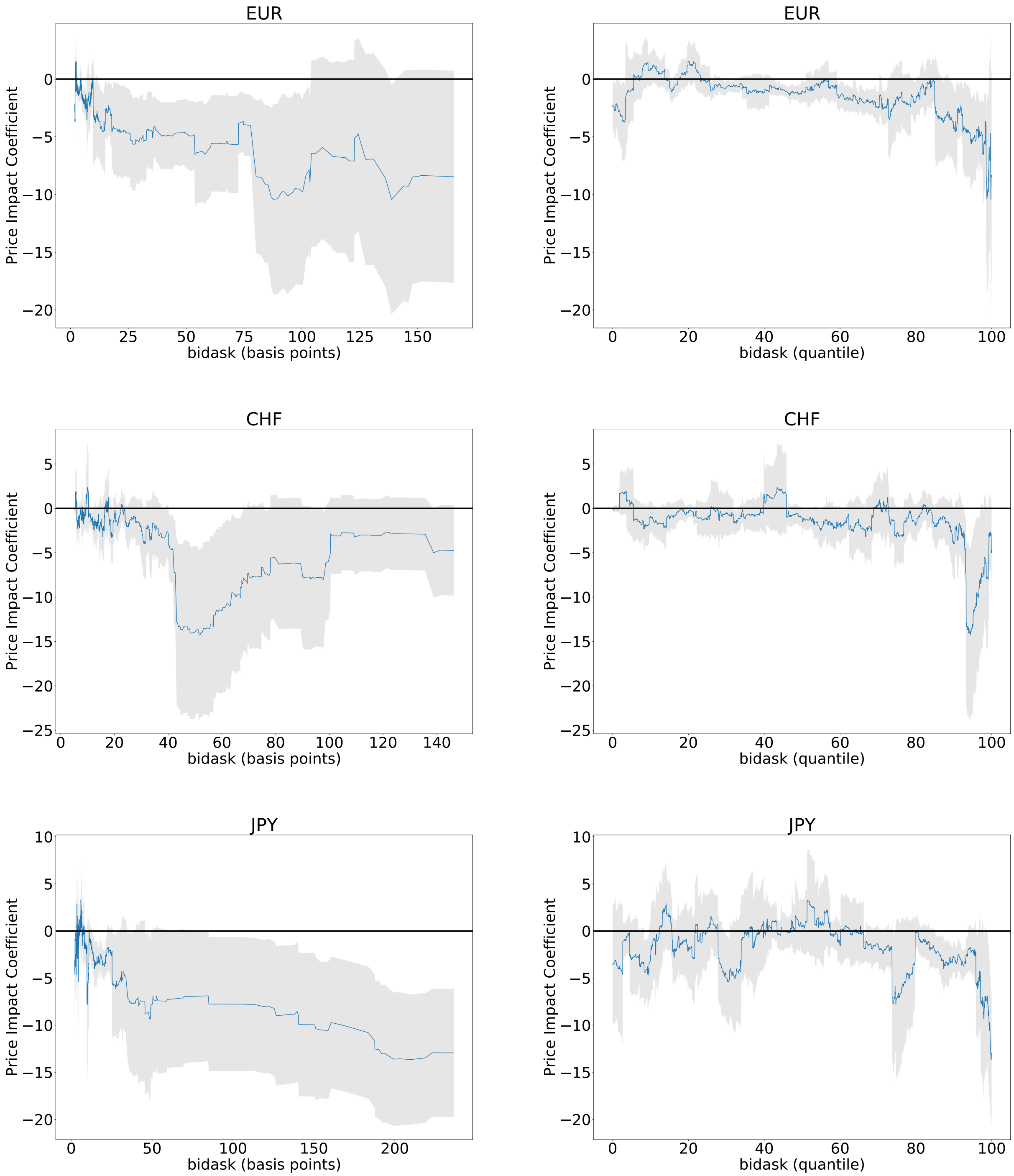
Note: This figure plots the impulse response of the change in CIP deviations to a 1 standard deviation shock to order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps, based on a bivariate VAR following Hasbrouck (1991) and Ranaldo and Somogyi (2019). Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs 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 EUR/USD, CHF/USD and JPY/USD in the pre-2008 period, and the right panel shows the response in the post-2008 period. Total sample period is from 01/2005-09/2017. Gray area denotes a standard error band equivalent for statistical significance at the 10% level.

Figure 11: Rolling regressions sorted on the range of LIBOR quotes: plot of price impact coefficients



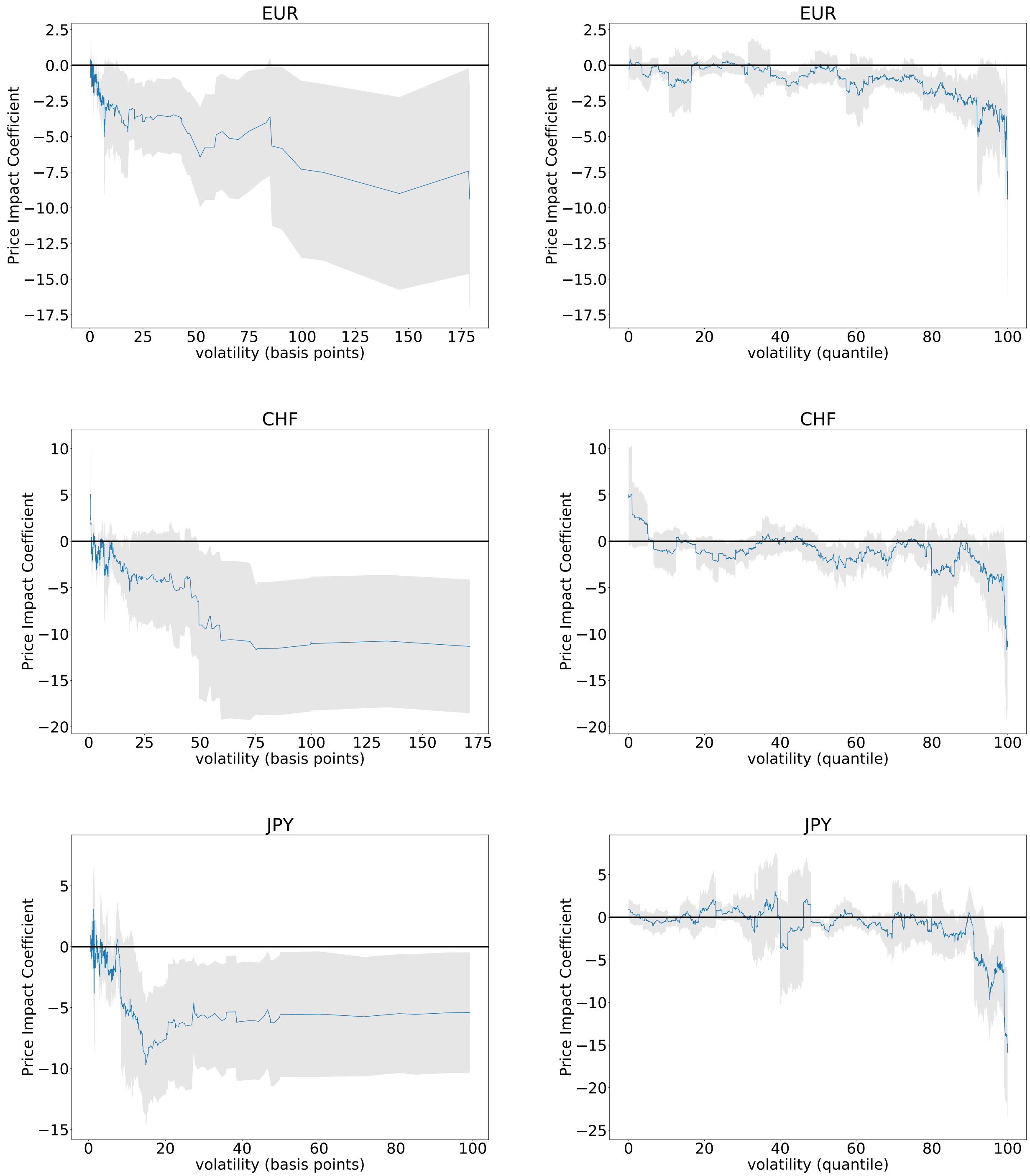
Note: This figure plots the price impact coefficients of rolling regressions of order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Rolling regressions are estimated using a window of 180 days. Data is sorted in ascending order by funding heterogeneity, which measures daily dispersion in individual panel bank's 3-month Libor quotes. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate, and a dummy for periods when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Gray area denotes 95% confidence interval using White heteroscedasticity-robust standard errors.

Figure 12: Rolling regressions sorted on bid-ask spreads: plot of price impact coefficients



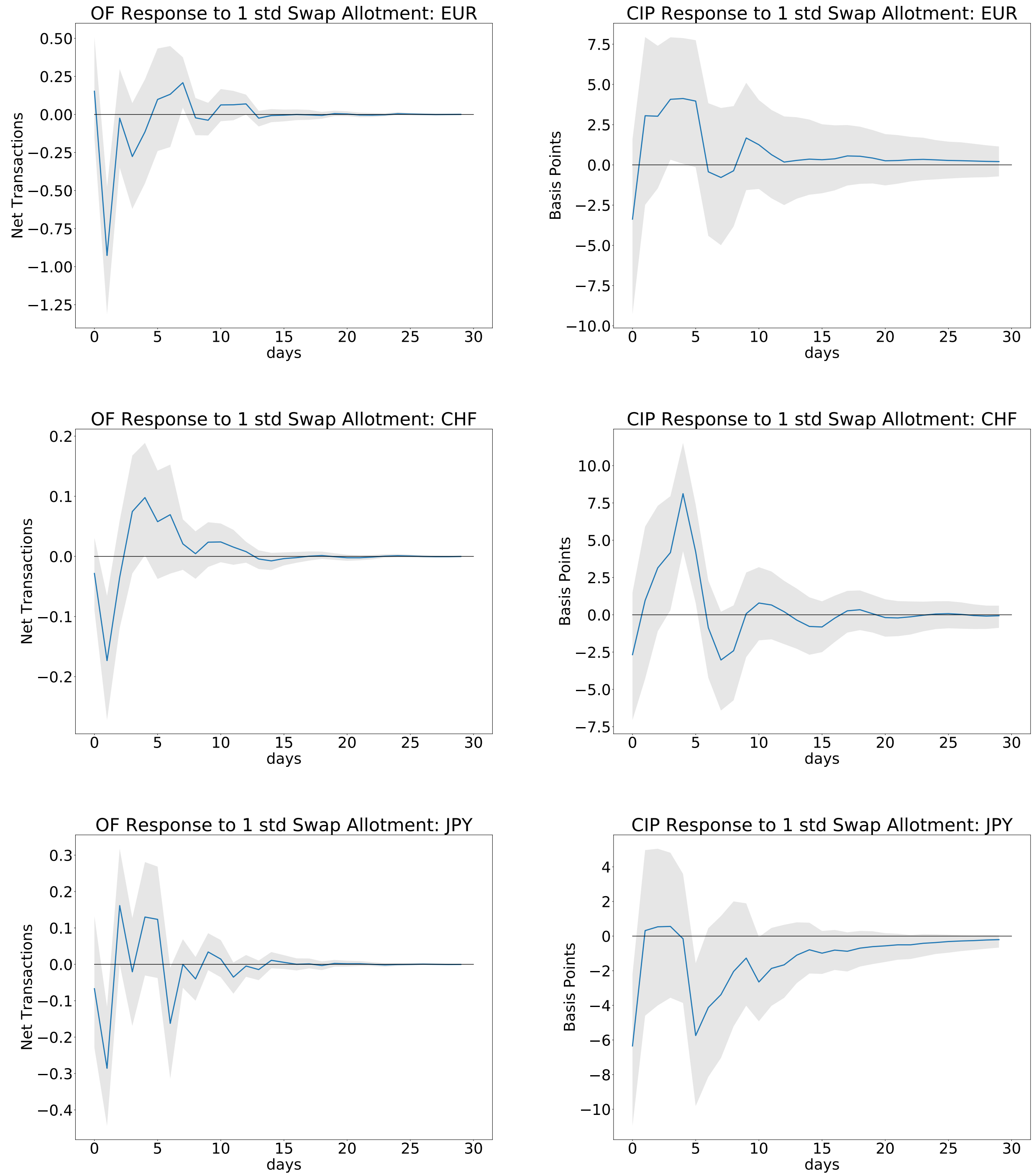
Note: This figure plots the price impact coefficients of rolling regressions of order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Rolling regressions are estimated using a window of 180 days. Data is sorted in ascending order by bid-ask spreads. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate, and a dummy for periods when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Gray area denotes 95% confidence interval using White heteroscedasticity-robust standard errors.

Figure 13: Rolling regressions sorted on intra-day volatility of forward rate: plot of price impact coefficients



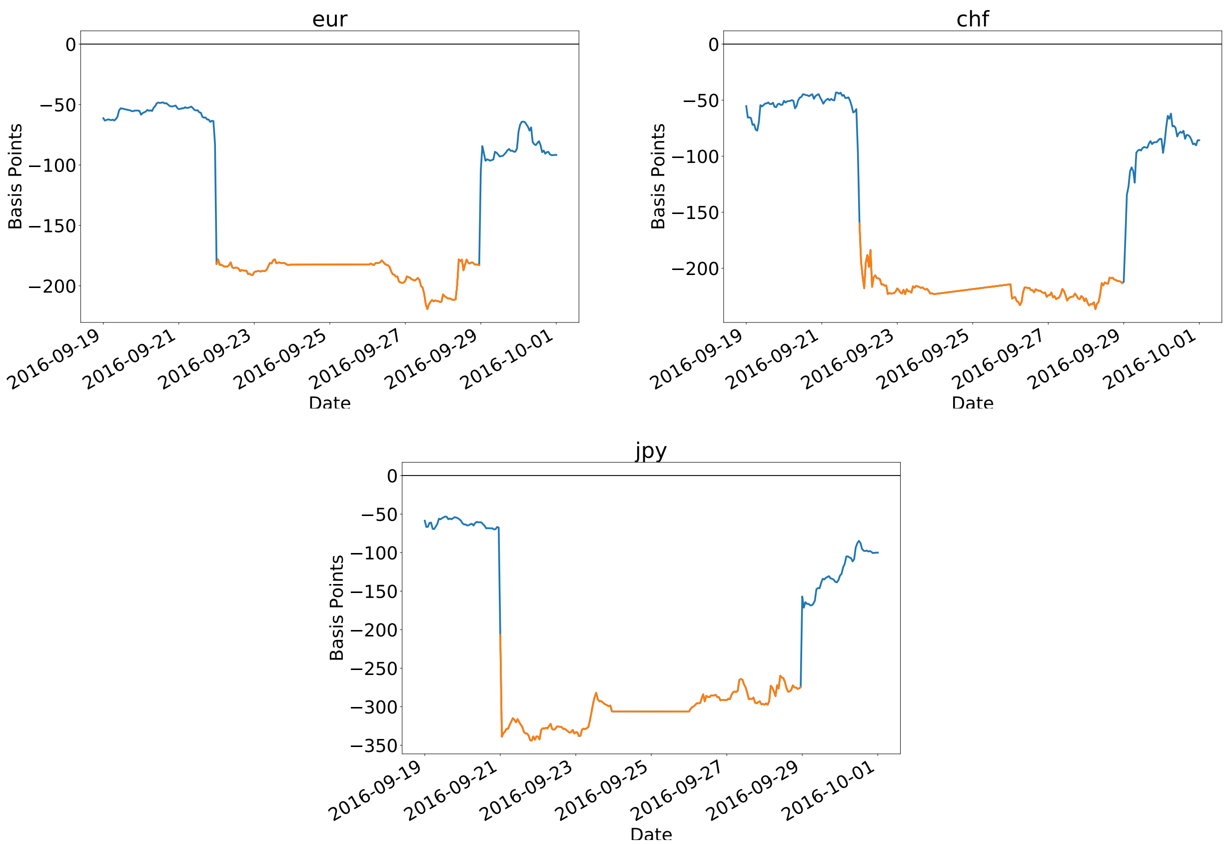
Note: This figure plots the price impact coefficients of rolling regressions of order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Rolling regressions are estimated using a window of 180 days. Data is sorted in ascending order by intra-day volatility of the forward rate. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate, and a dummy for periods when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Gray area denotes 95% confidence interval using White heteroscedasticity-robust standard errors.

Figure 14: CIP and OF Response to 1 std change in Swap Line Allotments



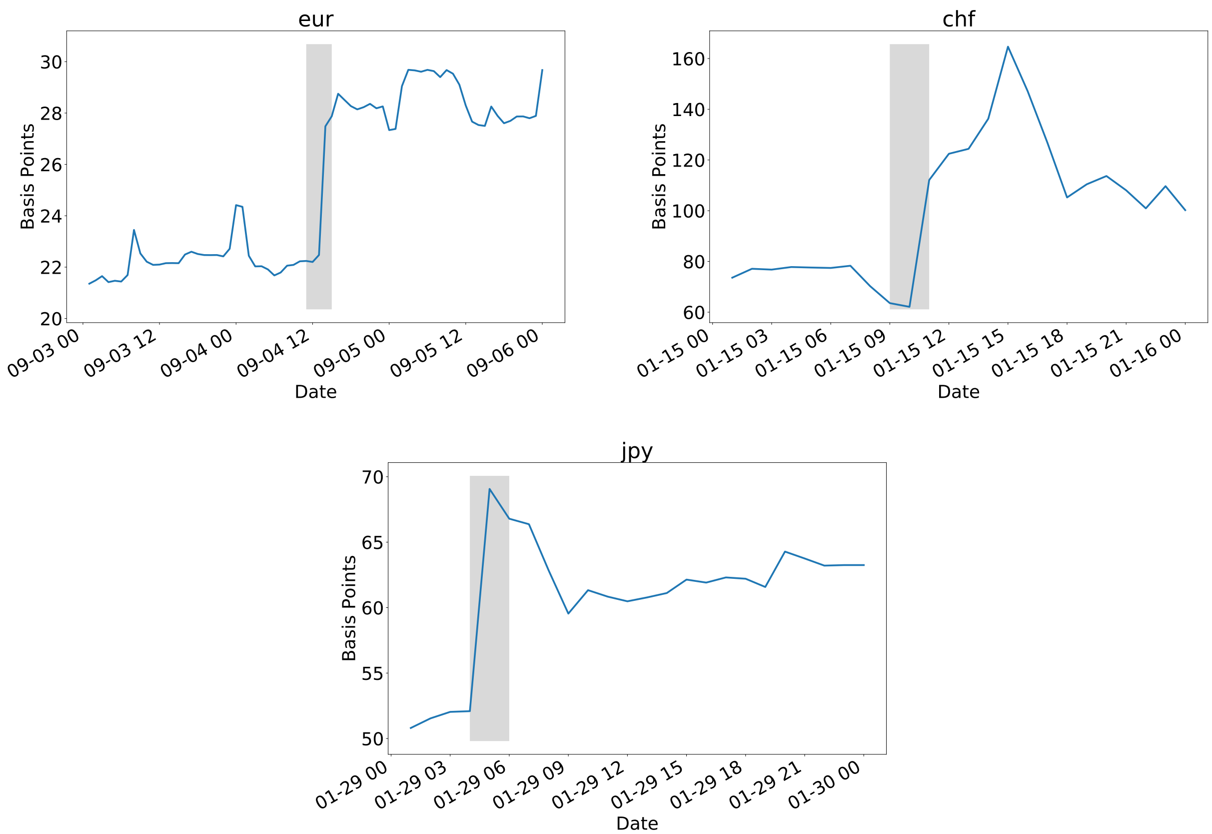
Note: This figure plots the impulse response of the change in CIP deviations and order flow to a 1 standard deviation shock in swap line allotments for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps, based on a multivariate VAR following Hasbrouck (1991) and Ranaldo and Somogyi (2019). Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs 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 EUR/USD, CHF/USD and JPY/USD 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 15: 1 week EUR/USD, CHF/USD and JPY/USD CIP deviations during quarter-end in September 2016



Note: This figure examines 1 week CIP deviations for the EUR/USD, CHF/USD and JPY/USD 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, using intra-day data from Thomson Reuters Tick History

Figure 16: Response of the forward premium of EUR/USD, CHF/USD and JPY/USD pairs to scheduled monetary announcements of the ECB, SNB and BOJ



Note: This figure shows the response of 1 week forward premium in EUR/USD, CHF/USD and JPY/USD 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
EUR/USD	-2.33	10.3	-120.0	5.1	-28.5	38.7	-621.9	73.1
CHF/USD	-8.1	17.0	-213.3	10.3	-34.0	42.7	-500.6	54.9
JPY/USD	-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 EUR/USD, CHF/USD and JPY/USD 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
EUR/USD	0.00	3.91	-16	29	-.09	3.25	-24	18
CHF/USD	0.08	1.59	-8	8	0.11	1.01	-10	7
JPY/USD	0.06	1.63	-7	8	0.00	1.41	-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 sample period is from 01/2005-09/2017.

Table 3: Price impact of order flow before and after GFC

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Pre 2008				Post 2008			
	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}
OF	-0.16	-0.42**	-0.41	-0.01	-3.64***	-3.74***	-2.98***	-4.42***
	(0.33)	(0.18)	(0.41)	(0.96)	(0.55)	(0.89)	(0.85)	(1.05)
Constant	-0.01	-0.10	0.05	0.05	-0.02	-0.22	0.24	-0.13
	(0.35)	(0.24)	(0.50)	(0.93)	(0.27)	(0.45)	(0.48)	(0.47)
Observations	2,084	713	712	659	6,703	2,238	2,234	2,231
R-squared	0.00	0.01	0.00	0.01	0.08	0.11	0.04	0.09
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, and the USD Trade weighted exchange rate. The full sample from Jan 1, 2005 to Sep 1, 2017 is split into pre and post 2008. Data is daily. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level. Standard errors for panel specification in columns (1) and (5) are clustered at the bilateral pair level.*

Table 4: Price impact of order flow; funding constraints and quarter-ends

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Pre 2008				Post 2008			
	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}
OF	-0.46	-0.47**	-0.50	-0.57	-1.04**	-1.20**	-2.02*	0.06
	(0.31)	(0.20)	(0.45)	(0.94)	(0.48)	(0.47)	(1.03)	(0.60)
OF × $D_{FundingHet}$	6.00	0.91	0.32	37.08	-4.14***	-4.84**	-0.34	-6.36***
	(6.46)	(4.30)	(2.30)	(26.70)	(1.18)	(2.17)	(1.57)	(1.68)
OF ×$Qend$	1.54	-0.13	0.29	3.16	-9.27***	-2.83	-9.09*	-15.97***
	(1.40)	(0.57)	(0.82)	(3.88)	(3.26)	(2.95)	(5.32)	(6.06)
Constant	0.13	0.03	-0.04	0.48	0.39*	0.24	0.92**	0.19
	(0.36)	(0.25)	(0.52)	(0.96)	(0.21)	(0.28)	(0.41)	(0.37)
Observations	2,084	713	712	659	6,703	2,238	2,234	2,231
R-squared	0.01	0.01	0.01	0.04	0.11	0.13	0.07	0.16
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. $D_{FundingHet}$ is a dummy variable that takes the value 1 when the daily dispersion in individual panel bank's 3-month Libor quotes is among the 25 per cent largest values, and zero otherwise. Qend is a dummy variable taking the value 1 when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Additionally, the following variables are included in the regression specification but not shown in the Table; Qend and $D_{FundingHet}$. Data is daily. The sample runs from Jan 1, 2005 to Sep 1, 2017. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level. Standard errors for panel specification in columns (1) and (5) are clustered at the bilateral pair level.*

Table 5: Price impact of order flow; direction of flow

	(1) ΔCIP_{panel}	(2) ΔCIP_{eur}	(3) ΔCIP_{chf}	(4) ΔCIP_{jpy}	(5) ΔCIP_{panel}	(6) ΔCIP_{panel}
OF × $\mathbb{1}[OF > 0]$	-0.12	-1.22*	-0.28	0.97	-0.88	-1.42*
	(0.67)	(0.67)	(0.35)	(2.13)	(0.60)	(0.72)
OF × $\mathbb{1}[OF < 0]$	0.38	0.02	-0.25	1.26	0.01	-0.86
	(0.47)	(0.51)	(0.95)	(0.97)	(0.47)	(0.86)
OF × $\mathbb{1}[OF > 0]$ × post2008	-4.39***	-5.07**	-2.58*	-6.04*		
	(1.23)	(2.31)	(1.38)	(2.77)		
OF × $\mathbb{1}[OF < 0]$ × post2008	-3.30***	-1.32	-2.99**	-5.32		
	(1.01)	(1.03)	(1.51)	(2.58)		
OF × $\mathbb{1}[OF > 0]$ × $D_{FundingHet}$					11.25*	-5.31**
					(6.23)	(2.20)
OF × $\mathbb{1}[OF < 0]$ × $D_{FundingHet}$					5.89	-2.83*
					(7.46)	(1.65)
OF × $\mathbb{1}[OF > 0]$ × Qend					3.43	-6.98*
					(2.42)	(4.24)
OF × $\mathbb{1}[OF < 0]$ × Qend					-0.96	-12.33*
					(1.28)	(7.48)
Constant	0.10	0.36	-0.02	-0.02	0.41	0.50
	(0.51)	(0.50)	(0.52)	(1.35)	(0.52)	(0.34)
Observations	8,787	2,951	2,946	2,890	2,084	6,703
R-squared	0.05	0.10	0.03	0.04	0.01	0.11
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Post2008					No	Yes

*Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. $\mathbb{1}[OF > 0]$ takes the order flow value if the order flow is positive, zero otherwise. Positive order flow implies a pressure to obtain USD spot and sell USD forward (i.e. borrow USD). $\mathbb{1}[OF < 0]$ takes the order flow value if the order flow is negative, zero otherwise. $D_{FundingHet}$ is a dummy variable that takes the value 1 when the daily dispersion in individual panel bank's 3-month Libor quotes is among the 25 per cent largest values, and zero otherwise. Qend is a dummy variable taking the value 1 when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Post 2008 is a dummy that takes the value 1 after Jan 1 2008, and zero otherwise. The Table only shows the relevant coefficients. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Additionally, the dummies for $D_{FundingHet}$, Qend and Post2008 are included, but not shown. Data is daily. The sample runs from Jan 1, 2005 to Sep 1, 2017. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level. Standard errors for panel specification in columns (1), (5) and (6) are clustered at the bilateral pair level.*

Table 6: Bid/ask spreads

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Pre 2008			Post 2008					
	EUR	CHF	JPY	EUR	CHF	JPY	EUR	CHF	JPY
$D_{FundingHet}$	0.02	14.05***	2.21**	10.95***	5.07***	13.39***	17.40***	10.13***	18.67***
	(0.19)	(2.08)	(1.09)	(0.95)	(0.89)	(1.13)	(1.59)	(1.32)	(1.95)
Qend	0.01	-0.41	0.27	3.64***	3.59**	4.81**	2.69	0.61	3.25
	(0.05)	(0.53)	(0.34)	(1.33)	(1.70)	(1.91)	(1.63)	(1.48)	(2.44)
post2015							-2.16***	10.74***	2.32***
							(0.28)	(1.40)	(0.40)
post2015 × Qend							2.57	10.68**	5.36*
							(2.36)	(4.97)	(2.98)
post2015 × $D_{FundingHet}$							-13.53***	-17.89***	-13.50***
							(1.63)	(2.01)	(2.01)
Constant	2.51***	9.56***	4.52***	5.61***	16.54***	6.11***	6.06***	14.53***	5.71***
	(0.01)	(0.15)	(0.07)	(0.18)	(0.42)	(0.19)	(0.22)	(0.39)	(0.23)
Observations	756	745	691	2,434	2,437	2,438	2,434	2,437	2,438
R-squared	0.00	0.12	0.02	0.10	0.02	0.10	0.17	0.07	0.13

*Note: This table regresses bid/ask spreads for 1 week FX swap quotes based on high frequency data from Thomson Reuters Tick History database on dummies for Funding Heterogeneity ($D_{FundingHet}$) and dates when the 1 week contract crosses quarter-ends (Qends) for three currency pairs (EUR/USD, CHF/USD and JPY/USD). Column (1) to (3) depict the results from a sample that runs from January 1,2005 to December 31, 2007, while column (4) to (6) are based on a sample period that runs from January 1, 2008 to September 1, 2017. In column (7) to (9) the interaction terms between a dummy that takes the value 1 from January 1, 2005 and onwards (zero otherwise) and funding heterogeneity and quarter-ends are added. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 7: Price volatility

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Pre 2008			Post 2008					
	EUR	CHF	JPY	EUR	CHF	JPY	EUR	CHF	JPY
$D_{FundingHet}$	0.04***	0.03***	0.07**	0.04***	0.02***	0.03***	0.06***	0.04***	0.03***
	(0.01)	(0.01)	(0.03)	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)	(0.00)
Qend	0.00	0.01	0.01*	0.04***	0.03***	0.05***	0.02**	0.01	0.02**
	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
post2015							-0.01***	0.02***	0.01***
						(0.00)	(0.01)	(0.00)	
post2015 × Qend							0.08***	0.07***	0.14***
						(0.03)	(0.03)	(0.03)	
post2015 × $D_{FundingHet}$							-0.04***	-0.07***	-0.02***
						(0.01)	(0.01)	(0.01)	
Constant	0.01***	0.02***	0.02***	0.02***	0.05***	0.02***	0.02***	0.05***	0.02***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Observations	756	745	691	2,434	2,437	2,396	2,434	2,437	2,396
R-squared	0.05	0.03	0.05	0.05	0.02	0.08	0.08	0.05	0.15

*Note: This table regresses daily price volatility for 1 week FX swap quotes based on high frequency data from Thomson Reuters Tick History database on dummies for Funding Heterogeneity ($D_{FundingHet}$) and dates when the 1 week contract crosses quarter-ends (Qends) for three currency pairs (EUR/USD, CHF/USD and JPY/USD). Column (1) to (3) depict the results from a sample that runs from January 1,2005 to December 31, 2007, while column (4) to (6) are based on a sample period that runs from January 1, 2008 to September 1, 2017. In column (7) to (9) the interaction terms between a dummy that takes the value 1 from January 1, 2005 and onwards (zero otherwise) and funding heterogeneity and quarter-ends are added. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 8: Price impact of order flow; bid-ask spreads

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Bid-ask spreads				Forward rate volatility			
	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}	ΔCIP_{panel}	ΔCIP_{eur}	ΔCIP_{chf}	ΔCIP_{jpy}
OF	-0.34	-0.89**	0.15	-0.39	-0.13	-0.58*	0.30	0.03
	(0.29)	(0.42)	(0.52)	(1.19)	(0.25)	(0.31)	(0.44)	(0.35)
OF $\times D_{spread}$	-5.28***	-4.64**	-5.24***	-5.77***				
	(0.37)	(2.07)	(1.77)	(1.83)				
OF $\times Qend$	-10.40	-3.21	-10.84**	-17.32***	-6.07	-2.38	-10.45**	-6.86
	(4.43)	(3.26)	(5.08)	(5.97)	(2.40)	(3.33)	(5.01)	(6.00)
OF $\times D_{vol}$					-5.17***	-5.33***	-6.01***	-4.19***
					(0.45)	(2.05)	(1.81)	(1.10)
Constant	0.36	0.38	0.78**	-0.06	0.59	-0.08	1.23	0.49
	(0.20)	(0.27)	(0.38)	(0.40)	(0.30)	(0.84)	(0.90)	(0.80)
Observations	6,703	2,238	2,234	2,231	6,663	2,238	2,234	2,191
R-squared	0.11	0.13	0.08	0.16	0.08	0.13	0.08	0.06
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Post2008	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. D_{spread} is a dummy variable that takes the value 1 when the daily forward rate bid-ask spread is among the 25 per cent largest values, and zero otherwise. D_{vol} is a dummy variable that takes the value 1 when the daily intra-day volatility of the forward rate is among the 25 per cent largest values, and zero otherwise. Qend is a dummy variable taking the value 1 when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Data is daily. The sample runs from Jan 1, 2008 to Sep 1, 2017. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level. Standard errors for panel specification in columns (1) and (5) are clustered at the bilateral pair level.*

Table 9: Price impact of order flow; swap line auctions

	(1) ΔCIP_{eur}	(2) ΔCIP_{chf}	(3) ΔCIP_{jpy}
OF	-5.97***	-0.42	-5.92***
	(2.11)	(0.62)	(2.05)
$D_{swapline}$	0.76	-1.13	0.11
	(1.76)	(1.21)	(1.66)
OF $\times D_{swapline}$	5.07**	-1.88*	5.29**
	(2.20)	(1.00)	(2.34)
qend	-3.55	-5.07*	-6.17*
	(2.24)	(2.93)	(3.66)
qend $\times OF$	-3.26	-5.18	-11.77**
	(2.58)	(3.85)	(5.58)
Constant	-0.52	1.68	0.41
	(1.78)	(1.13)	(1.52)
Observations	2,951	2,946	2,890
R-squared	0.10	0.04	0.06
Controls	Yes	Yes	Yes

*Note: This table regresses order flow for 1 week EUR/USD, CHF/USD and JPY/USD FX swaps on daily changes in 1 week CIP deviations based on Libor rates. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. The 1 Week CIP deviation is calculated using TR tick history quotes on 1 week spot and forward rates with close at 5 pm London time. $D_{swapline}$ is a dummy variable that takes the value 1 when there are net positive swap line auctions of dollars made to the central banks of the European Central Bank, Bank of Japan and Swiss National Bank, and zero otherwise. Qend is a dummy variable taking the value of 1 when the 1 week contract is settled prior to quarter-end and matures after quarter-end. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Data is daily. The sample runs from Jan 1, 2005 to Sep 1, 2017. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level.*

Table 10: Effect on order flow; Swap Lines

	(1)	(2)	(3)	(4)
	OF_{panel}	OF_{eur}	OF_{chf}	OF_{jpy}
SwapLines	-0.21**	-0.28*	-0.04	-0.50*
	(0.11)	(0.15)	(0.19)	(0.26)
Constant	0.03	-0.14*	0.18***	0.07
	(0.04)	(0.08)	(0.06)	(0.07)
Observations	1,444	480	482	482
R-squared	0.02	0.06	0.01	0.04
Controls	Yes	Yes	Yes	Yes

*Note: This table illustrates the impact of quarter-end on for 1 week order flow. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. SwapLine is a dummy variable that takes the value 1 on days when there was initial take up in any of the swap lines between the Fed and foreign central banks, zero otherwise. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Data is daily. The sample runs from Jan 1, 2008 to Dec 31, 2009. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level. Standard errors for panel specification in column (1) is clustered at the bilateral pair level.*

Table 11: Price adjustment quarter-end for EUR/USD, CHF/USD and JPY/USD

	EUR/USD				CHF/USD				JPY/USD			
Hour	2005-2007	2008-2013	2013-2015	2015-2017	2005-2007	2008-2013	2013-2015	2015-2017	2005-2007	2008-2013	2013-2015	2015-2017
-5	0	-0.5	0	0.3	-0.1	2.1	-0.2	-1.8	-0.2	0.1	-0.3	-0.3
-4	0.3	1	0	0.2	-0.2	1.8	-0.3	-0.1	0.2	1	-2.1	-0.3
-3	-0.1	-0.8	0.2	0.2	-0.1	-1	0.1	-3.3	-0.8	-0.9	-0.3	-0.5
-2	0.1	-0.2	2.1	1.7	0.2	-4.7	1.3	2.4	-0.8	2.2	-0.4	15.6
-1	0	0.9	0	9	1.3	2.7	-1.4	1.6	0.7	0.1	0.4	2.7
0	0.8	0.8	-1.6	22.7	0.2	2.3	-2.8	22.3	14.3	5.1	16.3	55.2
1	0.5	0	-0.4	6	-3.2	-3.2	2	16.2	-4.3	4.5	10.8	36
2	0.9	2.2	-0.3	0.8	0	1.1	-1.1	5.2	-1.2	4	-2.8	32.9
3	0.2	2.9	-0.2	0	-0.1	3.7	0.2	12.2	1.1	1.3	0.4	0
4	-0.1	0	-0.4	-0.7	0.4	-2	0.5	-2.2	-0.3	1	1.1	0.9
5	0.2	-0.4	0	0.1	-0.1	1.3	-0.7	-6.5	-0.2	0.2	0.7	10.3

Note: This table illustrates the hourly change in the FX swapped (synthetic) USD rate calculated from Libor from 5 hours before to 5 hours after the 1 week FX swap contract matures after quarter-end. 0 denotes the hour when the contract first matures after quarter-end. The numbers are in basis points and represent the average of all quarter-ends within the sample period.

Table 12: Effect on order flow; Quarter-end

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Pre 2008				Post 2008					
	OF_{panel}	OF_{eur}	OF_{chf}	OF_{jpy}	OF_{panel}	OF_{eur}	OF_{chf}	OF_{jpy}	OF_{panel}	OF_{panel}
Qend	0.14	-0.03	0.61***	-0.17	0.13***	0.15*	0.16**	0.08	0.22***	0.14**
	(0.10)	(0.14)	(0.18)	(0.19)	(0.05)	(0.09)	(0.07)	(0.08)	(0.08)	(0.06)
post2013									0.03	
									(0.03)	
post2013 × Qend									-0.29***	
									(0.10)	
post2015										-0.01
										(0.02)
post2015 × Qend										-0.02
										(0.09)
Constant	0.05**	-0.04	0.11***	0.07*	0.03**	-0.04*	0.11***	0.02	0.02	0.03**
	(0.02)	(0.04)	(0.04)	(0.04)	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Observations	2,095	724	712	659	6,723	2,240	2,241	2,242	6,723	6,723
R-squared	0.01	0.01	0.03	0.04	0.01	0.01	0.00	0.01	0.01	0.01
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Note: This table illustrates the impact of quarter-end on 1 week order flow. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. Qend is a dummy variable taking the value 1 when the 1 week contract is settled prior to quarter-end and matures after quarter-end, zero otherwise. Post2013 and post2015 are dummy variables that are 1 from Jan 2013 and Jan 2015, respectively, zero otherwise. Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Data is daily. The sample runs from Jan 1, 2008 to Sep 1, 2017. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level. Standard errors for panel specification in columns (1), (5), (9) and (10) are clustered at the bilateral pair level.*

Table 13: Effect on order flow; Monetary Policy surprises

	(1)	(2)	(3)	(4)
	OF_{panel}	OF_{eur}	OF_{chf}	OF_{jpy}
Δois	-1.86	-2.28	-1.18	13.86
	(1.59)	(3.84)	(1.85)	(10.07)
Constant	-0.05	0.02	-0.03	-0.09
	(0.05)	(0.07)	(0.11)	(0.09)
Observations	363	136	87	122
R-squared	0.01	0.04	0.02	0.09
Controls	Yes	Yes	Yes	Yes
Post2008	Yes	Yes	Yes	Yes

*Note: This table illustrates the impact of monetary policy surpirses on 1 week order flow. Standardized order flow OF is measuring the net buyer transactions of swapping euros, swiss francs and yen into dollars, and is sourced from TR D2000-2 inter-dealer trades for 1 Week FX swaps. ΔOIS is the 30 min change in the 1-month OIS rate (Overnight Index Swaps - a proxy for the risk free rate) in the respective currency around the central bank policy announcement. Monetary announcements in EUR, CHF, JPY and USD are considered. In the case of US announcements the sign of the change in the OIS is switched so that a positive change in the OIS always proxy an increase in the interest rate differential towards the US (i.e foreign currency rate minus the US rate). Controls include the changes in USD Libor-OIS spreads for 1 week and 3 month maturities, the VIX index, the USD Trade weighted exchange rate. Data is daily. The sample runs from Jan 1, 2008 to Sep 1, 2017. White heteroscedasticity-robust standard errors are reported in parentheses. *** denotes significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level. Standard errors for panel specification in column (1) is clustered at the bilateral pair level.*

Appendices

A: Model Appendix

Proof of proposition 1

First we take the market clearing condition in trading round 3.

$$\sum_{j=1}^{N} {x_{j,t,3}}^{*} = \int_0^1 f_{t,3}(\theta_b, \Delta_{t-1,3})db + OF_{t,2}$$

Substituting the equation for arbitrage in trading round 3, we obtain:

$$\sum_{j=1}^{N} \frac{\Delta_{t,3} - c_{j,t}}{\rho\sigma^2} = \int_0^1 f_{t,3}(\theta_b, \Delta_{t-1,3})db + OF_{t,2}$$

In period $t-1$, price-setting is governed by the market clearing condition in period $t-1$. We assume that order flow in the inter-dealer market in period $t-1$ is zero, so customer demands for dollars are met by arbitrageur supply.

$$\sum_{j=1}^{N} \frac{\Delta_{t-1,3} - c_{j,t}}{\rho\sigma^2} = \int_0^1 f_{t-1,3}(\theta_b, \Delta_{t-1,3})db$$

Subtracting equations for market clearing in the trading round 3 on periods t and $t-1$, and rearranging terms, we obtain the following expression for price-setting in the forward market, where $\bar{c}_{j,t} = \sum_{j=1}^{N} \frac{c_{j,t}}{N}$.

$$\Delta_{t,3} - \Delta_{t-1,3} = \bar{c}_{j,t} - \bar{c}_{j,t-1} + \frac{\rho\sigma^2}{N}\left(\int_0^1 f_{t,3}(\theta_b, \Delta_{t-1,3})db - \int_0^1 f_{t-1,3}(\theta_b, \Delta_{t-1,3})db\right) + \frac{\rho\sigma^2}{N} OF_{t,2}$$

The price-setting relation is linear in order flow, with intercept $\alpha = \bar{c}_{j,t} - \bar{c}_{j,t-1} + \frac{\rho\sigma^2}{N}\left(\int_0^1 f_{t,3}(\theta_b, \Delta_{t-1,3})db - \int_0^1 f_{t-1,3}(\theta_b, \Delta_{t-1,3})db\right)$ and slope $\beta = \frac{\rho\sigma^2}{N}$.

$$\Delta_{t,3} - \Delta_{t-1,3} = \alpha + \beta OF_{t,2}$$

Proof of proposition 2

The arbitrageur supply function has a leverage constraint.

$$x^*_{j,t} = \begin{cases} \frac{\Delta_t - c_{j,t}}{\rho\sigma^2} & ,\lambda_j = 0 \\ \gamma W_t & ,\lambda_j \neq 0 \end{cases}$$

I suppose a number of arbitrageurs N_ℓ have a tightening of leverage constraints ($\lambda_j \neq 0$, and supply a fixed amount of dollars in the FX swap market. The remaining $N - N_\ell$ arbitrageurs supply a linear function. Define the fraction of leverage constrained arbitrageurs as $\eta = \frac{N_\ell}{N}$.

$$\sum_{j=1}^{N-N_\ell} \frac{\Delta_{t,3} - c_{j,t}}{\rho\sigma^2} + N_\ell \gamma W = \int_0^1 f_{t,3}(\theta_b, \Delta_{t-1,3})db + OF_{t,2}$$

In the prior period, assume the leverage constraints did not bind, and market clearing required the following.

$$\sum_{j=1}^{N} \frac{\Delta_{t-1,3} - c_{j,t}}{\rho\sigma^2} = \int_0^1 f_{t-1,3}(\theta_b, \Delta_{t-1,3})db$$

Subtracting equations for market clearing in the trading round 3 on periods t and $t-1$, and rearranging terms, we obtain the following expression for price-setting in the forward market, where $\bar{c}_{j,t} = \sum_{j=1}^{N} \frac{c_{j,t}}{N}$.

$$\Delta_{t,3} - \frac{1}{1-\eta}\Delta_{t-1,3} = c_{j,t} - \frac{N}{N-N_\ell}c_{j,t-1} + \\ \frac{\rho\sigma^2}{N}\left(\int_0^1 f_{t,3}(\theta_b, \Delta_{t-1,3})db - \frac{N}{N-N_\ell}\int_0^1 f_{t-1,3}(\theta_b, \Delta_{t-1,3})db\right) + \frac{\rho\sigma^2}{N(1-\eta)}OF_{t,2}$$

The price-setting relation is linear in order flow, with intercept $\alpha = \bar{c}_{j,t} - \frac{1}{1-\eta}\bar{c}_{j,t-1} + \frac{\rho\sigma^2}{N}\left(\int_0^1 f_{t,3}(\theta_b, \Delta_{t,3})db - \frac{1}{1-\eta}\int_0^1 f_{t-1,3}(\theta_b, \Delta_{t-1,3})db\right)$, where $\bar{c}_{j,t} = \sum_{j=1}^{N} \frac{c_{j,t}}{N}$
and slope $\beta = \frac{\rho\sigma^2}{N(1-\eta)}$.

$$\Delta_{t,3} - \Delta_{t-1,3} = \alpha + \beta OF_{t,2}$$