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# The failure of covered interest parity: FX hedging demand and costly balance sheets*

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### Abstract

The failure of covered interest parity (CIP), or, equivalently, the persistence of cross-currency basis, in tranquil markets has posed a puzzle. By analysing the term structure of CIP deviations, we empirically establish that imbalances in the demand for and supply of FX hedges exert first order effects on the level of CIP deviations. Fluctuations in FX hedging demand move forward exchange rates out of line with CIP because, in aggregate, financial institutions charge a premium for provisioning for risks associated with exposures to FX derivatives needed to supply FX hedges. We also find that the elasticity of CIP deviations to changes in FX hedging demand can be explained with proxies for FX collateral risk. Our findings point to a fundamental change in the relationship between prices and quantities in FX derivatives markets on which CIP is predicated, suggesting that the notion of CIP as a no-arbitrage condition may be obsolete.



JEL Classification: F31, G15, G2

Keywords: Covered interest parity, FX swaps, currency basis, limits to arbitrage, US dollar funding, currency hedging, preferred habitat investors, term structure.

# I. Introduction

One of the most notable financial market anomalies in the post-global financial crisis (GFC) period has been the violation of the no-arbitrage condition known as covered interest parity (CIP), or, equivalently the persistence of the cross-currency basis, in a period characterized by low volatility and absence of a major credit strains. A distinguishing feature of the post-GFC CIP violations is the persistence of longer-term deviations in the pricing of currency swaps and longer-term forwards. The recent and growing literature on CIP deviations has not converged on the first-order drivers of the persistent level of CIP deviations, and pays little attention to longer-term deviations. This paper provides an explanation for the sign and persistence of long-term CIP deviations. In contrast to the textbook notion of CIP, we first show that quantities of FX hedging demand affect prices of FX derivatives leading to CIP violations. We construct measures of the relevant FX hedging imbalances and find that their direction and size explains the sign and magnitude of currency basis against the USD. This finding calls the long-standing interpretation of CIP as a no-arbitrage condition into question.

The correlation between CIP deviations and FX hedging imbalances arises due to balance sheet costs on the supply side of FX hedges. The costs are incurred when entering into FX derivatives transactions in order to engage in "CIP arbitrage."[1] Balance sheet costs of taking advantage of CIP violations arise because virtually all FX derivatives are traded over-the-counter (OTC), exposing counterparties to FX collateral risk. For USDJPY, for example, our estimates indicate that over $1 trillion in FX collateral is tied up to support FX hedging activity. Managing this risk introduces a marginal cost of being on the supply side of FX hedges, which is priced into FX derivatives as a result. Consequently, the forward discount or premium can widen beyond the band that defines CIP, depending on the sign of FX hedging imbalances. These frictions can be greater for longer maturity contracts. To this end, we pay special attention to the term structure of the currency basis, using principal component analysis (PCA), allowing us to identify the most important factors driving the persistence in the *level* of CIP deviations versus the secondary transitory factors behind occasional disturbances to the *slope* of CIP deviations. Most of the literature has implicitly focused on the latter. Yet, the first PCA component capturing the level explains most of the variation of the currency basis term structure for the EURUSD, USDJPY, and AUDUSD. Therefore, any

[1] The quotes are used to emphasize that the concept of a self-financed riskless arbitrage may no longer apply.

proposed economic drivers of the currency basis should exhibit a close association with the level factor. We identify first order, level, effects of the currency basis arising from imbalances in the demand and supply of FX hedges; and second order, slope, effects, arising from temporary USD funding shortages and quarter- and year-end dislocations in money markets. It is important to note here that the persistent CIP deviations characteristic of the post-crisis period preceded the quarter-end liquidity anomalies (that have garnered a lot of attention) and therefore cannot be fully explained by them.

Two propositions emerge as a result of our term structure analysis. First, FX hedging demand and the level of CIP deviations exhibit a strong and statistically significant long-run relationship. Second, that temporary shocks to bank credit risk and liquidity dislocations in money markets cause temporary spikes in CIP deviations at the short-end, manifested as temporary inversions in the *slope* of the CIP term structure. Our estimation results, using an error correction model, confirm these propositions. Our final proposition draws on a theoretical framework in the lens of a preferred-habitat limits to arbitrage model. We derive a market clearing FX forward rate that clearly shows the channel by which demand for FX hedges affects the pricing of FX/cross-currency basis swaps and prevents CIP from holding. Specifically, the elasticity of CIP deviations to FX hedging demand depends on the interaction of market and counterparty risk, which give rise to FX collateral risks inherent in OTC FX derivatives. We validate our model by estimating the elasticity of currency basis to FX hedging demand using Kalman filter regressions and relating it to the above-mentioned underlying economic risk factors. We conclude by discussing how these economic risks are treated in risk management practices and regulatory requirements.

Hence, our evidence points at the importance of frictions specific to banks' intermediation in FX derivatives markets as the main explanation for the persistence of CIP deviations in a non-crisis environment. That said, there could be additional factors not addressed in this paper that exacerbate CIP violations. Furthermore, our framework says little about CIP violations at the short end, that are closely tied to frictions in money markets except that these are transient and largely orthogonal to the persistent CIP deviations at longer maturities. Finally, this paper addresses the empirical drivers of the violation of the law-of-one-price (LOOP) stipulated by CIP, but does not attempt to measure the profitability of arbitrage opportunities that may arise for some market participants due to this failure.

The rest of the paper is organized as follows: Section II reviews related literature. Section III provides the institutional background on FX derivatives and their relationship to CIP and describes key characteristics of demand for FX hedges (including a description of our quantity data) and supply of FX hedges ("CIP arbitrage"). Section IV discusses the empirical and economic drivers of the term structure of CIP deviations; Section V presents our empirical analysis of long- and short-run drivers of CIP deviations. We present our theoretical framework in Section VI and provide empirical validation of the model and its relationship regulation and risk management in Section VII. Section VIII concludes.

## II. Related literature

Many studies have examined CIP deviations before the crisis, during the crisis, and in the more recent period of post-crisis 'calm'. Pre-GFC, Akram, Rime, and Sarno (2008) found that deviations disappear almost instantly, with the exception of temporary episodes when arbitrage was inhibited by bank counterparty risk.[2] During the GFC, CIP deviations were wide, driven again by bank counterparty risk as well as wholesale US dollar funding strains (Baba, McCauley, and Ramaswamy (2009), Coffey, Hrung, and Sarkar (2009), McGuire and von Peter (2012), Baba and Packer (2009)). Additionally, Bottazzi, Luque, Pascoa, and Sundaresan (2012) and Ivashina, Scharfstein, and Stein (2015) explore the widening of CIP deviations during the euro area sovereign debt crisis as a result of further dollar funding shortages. The former posit that CIP deviations arise due to USD collateral shortage; the latter that CIP deviations can arise when banks shift some of their funding away from wholesale dollar funding markets due to default risk premia.[3] These studies all focus on CIP deviations associated with short tenors (typically 1-month) because these have largely characterized dislocations during crises.

The re-emergence of the CIP violations in the period of relative calm post-crisis since mid-2014 has led to important new studies. Du, Tepper, and Verdelhan (2018) establish CIP violations that cannot be explained away by credit risk or transaction costs. They infer the presence of balance sheet costs from quarter-end anomalies and IOER-Fed funds arbitrage, and provide empirical

[2] For instance, Hanajiri (1999) documents the so-called "Japan premium" during the Japan banking crisis in the 1990s.

[3] A similar theoretical framework to Ivashina, Scharfstein, and Stein (2015) is also used in He, Wong, Tsang, and Ho (2015) to study the implications of monetary policy divergence on international dollar credit; however, the authors take the cross-currency basis as exogenous to international banks' US dollar funding.

findings that the basis is correlated with interest rates and monetary policy shocks. Du, Tepper, and Verdelhan (2018) argue that balance sheet constraints are at play, especially the leverage ratio constraint on short-term USDJPY FX swaps around quarterly reporting periods. Specifically, they document that 1-week, 1-month, and 3-month CIP deviations widen as the corresponding FX swap contract maturities cross the quarter end dates. However, they do not provide rigorous supporting evidence for any particular balance sheet channel. Cenedese, Della Corte, and Wang (2018) are among the first to examine actual trading activity by different market participants and how this relates to CIP deviations and balance sheets costs. For short maturities, they find that lower leverage ratio buffer of major bank dealers is associated with wider CIP deviations in the following quarter. At the same time, for longer duration (>1 year maturity) contracts, the authors find that the widening of the basis is associated with regulatory capital ratios, and not the leverage ratio, consistent with longer-term contracts having a higher risk-weight in the risk-weighted assets (RWA)-type balance sheet constraint, as highlighted by Du, Tepper, and Verdelhan (2018). Krohn and Sushko (2017) draw on dealer level FX swap quote data to show that quarter- and year-end widening in 1-month CIP deviations owes to the pull-back by globally-systemically important bank (G-SIB) dealers, who have the incentive to manage down their total exposure to FX swaps when it contributes to the G-SIB score calculation. Avdjiev, Du, Koch, and Shin (forthcoming), in turn, explore a link between the US dollar exchange rate and cross-currency basis, against a backdrop of the dollar exchange rate relating to the shadow price of bank leverage.

A strand of literature most closely related this paper combines some notion of limits to arbitrage with volumes or measures of activity by end-users of FX swap markets.[4] Cenedese, Della Corte, and Wang (2018) show that the leverage ratio of dealer banks contributes to CIP deviations through its interaction with customer order-flow. Iida, Kimura, and Sudo (2018) use sign restrictions to identify supply and demand shocks in the Tokyo FX swap market and find that interest rate differentials have replaced measures of banks' creditworthiness as drivers of CIP deviations in the USDJPY and EURJPY currency pairs. Bräuning and Ivashina (2016) study monetary policy shocks from the perspective of global banks' cross-currency investment and hedging of currency risk, similar to our paper. Similarly, Liao (2018) attributes CIP deviations primarily to the activities of foreign

[4] Among policy publications, Borio, McCauley, McGuire, and Sushko (2016) offer a framework to think about CIP violations in non-crisis times, stressing the combination of hedging demand and tighter limits to arbitrage while Arai, Makabe, Okawara, and Nagano (2016) show evidence of increased demand for US dollars in FX swaps against the background of diverging monetary policies, reduced appetite for market-making and arbitrage by global banks, and the developments in the flow of arbitrage capital in FX swap markets.

currency corporate bond issuers, drawing attention to the fact that, particularly the EURUSD, currency basis moves closely with corporate bond spreads over longer horizons (about 5 years).

Taking somewhat of a different angle, Rime, Schrimpf, and Syrstad (2017) focus on the short-end (3-months) and attribute CIP violations to market segmentation and differences in liquidity premia across currencies. Unlike most other studies that test the law-of-one-price (LOOP) interpretation of CIP (including ours), Rime, Schrimpf, and Syrstad (2017) also attempt to measure CIP arbitrage profits. They show that funding with USD financial commercial paper and investing in foreign currency T-bills or central bank deposit facilities means that CIP arbitrage profits can only be reaped by top-tier banks. Their test is extremely conservative because it assumes that arbitrage funding requires unsecured instruments (thus loading the funding costs with credit risk), and not secured instruments (free of credit risk) such as repo. It also assumes that the investment leg must use safe assets, such as short-term government bills or central bank deposits (which offer low or negative yields). Wong, Ng, and Leung (2017) and Wong and Zhang (2017) argue that the post-GFC pricing of currency forwards and swaps can be reconciled with money-market rates that are stripped of premia from counterparty risk.

Finally, our paper is related to the literature on OTC derivatives markets, which are opaque, complex, and highly segmented (Duffie (2012)). Cenedese, Ranaldo, and Vasios (2018) study interest rate swap markets, and find persistent OTC premia for contracts that are not centrally cleared. Given that none of the deliverable FX derivatives are centrally cleared, so that counterparties take direct bilateral risk exposures to each other, such premia are endemic in FX markets. Furthermore, unlike in interest rate swaps, counterparties in FX and currency swaps actually exchange the principal amounts, because these are denominated in two different currencies. Hence, the aggregate effect of OTC counterparty and market risk premia in FX derivatives is much larger. Consistent with higher post-crisis counterparty risk concerns among traditional FX market participants, Levich (2012) finds that trading in interbank currency forwards has declined in favour of currency futures. Because futures are traded on an exchange and counterparties post margins, they involve significantly lower counterparty risk than OTC forward contracts. Andersen, Duffie, and Song (forthcoming) and Duffie (2018) present a framework for how regulation affects dealer banks' pricing of OTC derivatives including FX and cross-currency basis swaps. In a similar vein, Hau, Hoffmann, Langfield, and Timmer (2017) and Abbassi and Brauning (2018) provide evidence that dealer pricing to clients in FX derivatives is highly discriminatory.

We contribute to this literature in several ways. First, we show that CIP deviations emerge due to FX hedging imbalances that are much more proximate than monetary policy announcements, levels of interest rates, or differences in credit spreads, which may be necessary, but not sufficient to explain CIP failure. Interest rates matter only to the extent that investors from jurisdictions with low domestic yields a) choose to invest in higher yielding foreign currency assets *and* b) hedge the associated currency risk using FX forwards, FX swaps, or cross-currency swaps. Absent a) *and* b), the levels of yields would not contribute to CIP violations. Similarly, differences in corporate credit spreads can explain CIP deviations only if a) corporates from high credit spread jurisdictions shift their funding to foreign currencies offering low credit spreads *and* b) swap the foreign currency funding back into domestic currency using FX/cross-currency basis swaps. Such activity has indeed taken place in EURUSD markets, for which the findings of Liao (2018) are most robust, but has been essentially absent in USDJPY, a currency pair which has been exhibiting the widest CIP deviation. In contrast, we show that the size and sign of FX hedging supply and demand imbalances in EURUSD, USDJPY, and AUDUSD can explain the sign and size of CIP deviations in these currency pairs.

Second, we present theoretical and empirical evidence for the specific source of balance sheet constraints that precludes self-funded, cost-less arbitrage from taking place. These constraints, as mentioned, have little to do with leverage regulation, but relate to RWA capital requirements and risk-management.

Third, our paper shows that factors such as money market frictions, including anomalies related to balance sheet management around leverage regulation, and funding and market liquidity indeed can drive short-term CIP deviations, and, hence, the slope of the term structure of CIP violations across maturities. However, we also show that these drivers are largely orthogonal to the persistent level of CIP deviations, which is driven by persistent imbalances in FX hedging markets.

Fourth, our paper sheds additional light on the determinants of prices in opaque OTC FX derivatives markets. Specifically, we provide an explanation, based on the term exposure of those supplying FX hedges via FX forwards, FX swaps, and cross currency swaps, for why the levels of FX forward rates, set by these instruments, deviate from CIP. The stock of the associated positions priced off of the currency forward rates supports trillions of dollars of cross-currency funding and hedging activity. Notional amounts outstanding of forwards, FX swaps, and currency swaps were

\$58 trillion as of end-December 2016, according to Borio, McCauley, and McGuire (2017), who also argue that the obligations to pay dollars incurred through FX swaps/forwards and currency swaps are functionally equivalent to secured debt. In line with their line of argument, our findings imply that forward FX transactions must be understood as bank credit and that the CIP hypothesis must be interpreted as a special case of balanced supply and demand or extremely lax credit conditions in cross-currency markets.

## III. Institutional background

### *A. CIP and the forward discount/premium*

Let us define a time-$t$ spot rate, $S_t$, and a time-$t$ forward rate with maturity $\tau$, $F_{t,\tau}$, in units of USD per foreign currency, a dollar benchmark time-$t$ interest rate, $R_{t,\tau}$, and a foreign currency benchmark time-$t$ interest rates, $R^*_{t,\tau}$. Foreign currencies considered in this paper are AUD, EUR, and JPY, and benchmark interest rates are taken to be Libor rates as these have served as the reference rates in cross currency basis swaps. CIP failure implies that synthetic USD rates deviate from actual USD money market rates:

$$\frac{F_{t,\tau}}{S_t}(1 + R^*_{t,\tau}) \neq 1 + R_{t,\tau}. \tag{1}$$

CIP deviations (or equivalently currency basis) are calculated by subtracting the left-hand side from the right-hand side in equation 1: by convention, when the synthetic USD rate is higher than the actual USD money market rate, the CIP deviation is negative. Figure 1 shows that this has been the case of both EUR and JPY, where the borrowing rate for USD via FX swaps and cross currency basis swaps has been expensive compared to the USD money market rate. Using Equation 1, this implies $F_{t,\tau} > S_t\left(\frac{1+R_{t,\tau}}{1+R^*_{t,\tau}}\right)$ for EUR and JPY, meaning that USD trades at a steeper forward discount than stipulated by CIP, thus generating an "arbitrage opportunity" for USD lenders in the swap market. The converse has been true for those looking to swap into USD out of AUD, where USD borrowers (AUD lenders) in the swap market have paid a lower synthetic USD rate compared to USD Libor rate. By equation 1, this implies $F_{t,\tau} < S_t\left(\frac{1+R_{t,\tau}}{1+R^*_{t,\tau}}\right)$, so that USD lenders have been earning less by locking-in $F_{t,\tau}$ via the swap compared to just investing their USD at the USD Libor.

[Figure 1, about here]

*B. FX swaps and cross-currency basis swaps*

Whether or not CIP holds thus largely depends on the forward exchange rate $F_{t,\tau}$, given the level of the prevailing spot exchange rate $S_t$ and interest rates $R_{t,\tau}$ and $R^*_{t,\tau}$. The level of $F_{t,\tau}$ in relation to $S_t$, in turn, is determined in FX forwards, FX swaps, and cross-currency basis swaps markets.

An FX swap is a contract in which one party borrows one currency from and simultaneously lends another to the second party at the spot rate $S_t$ in units of USD per foreign currency. At maturity, the amount borrowed is repaid at the pre-agreed FX forward rate $F_{t,\tau}$. The basis can be inferred by comparing the forward discount, $F_{t,\tau} - S_t$, with the chosen interest rate benchmark, typically Libor rates in the two currencies. A textbook notion of covered interest arbitrage is that borrowing in USD to invest in EUR is profitable if $(F_{t,\tau} - S_t)/S_t > (R_{t,\tau} - R^*_{t,\tau})$, where the difference between $R_{t,\tau}$ and $R^*_{t,\tau} + (F_{t,\tau} - S_t)/S_t$ constitutes the basis. FX swaps, which are short term, can be viewed as collateralized borrowing and lending. Baba, Packer, and Nagano (2008) provide a more detailed exposition of the cash flows in FX swaps and cross-currency swaps.

Cross-currency swaps are FX derivatives in which two parties borrow from and simultaneously lend to each other an equivalent amount of money denominated in two different currencies for a predefined period of time. A cross-currency basis swap is a floating/floating swap where the reference rates are Libor rates in the two currencies. At maturity date, the amount borrowed is exchanged back at the same spot exchange rate $S_t$. Thus, unlike an FX swap, which is priced off of the forward exchange rate, a cross-currency basis swap is priced off the respective Libor rates, whereby one counterparty stands to pay USD Libor plus (or minus) the time-$t$ basis with maturity $\tau$, $b_{t,\tau}$, for term borrowing of USD in exchange for its currency. Cross-currency basis swaps tend to be longer-term. For a hypothetical $\tau = 1$-period term, by a no-interest arbitrage condition, an FX swap desk's offer price for forward points will satisfy the following relationship with the currency basis: $F_{t,1} - S_t = S_t \times (1 + R_{t,\tau} + b_{t,1})/(1 + R^*_{t,\tau}) - S_t$.

FX forwards/swaps and cross currency swaps are the modal instruments in currency markets. According to BIS (2016), daily trading in FX swaps alone amounted to $2.4 trillion, accounting for 47% of total FX turnover. Adding forwards and currency swaps, the share rises to 63%. Institutional investors increased their trading in FX swaps by almost 80% between 2013 and

2016. Turnover in the longer-term currency swaps also increased by 79% between 2013 and 2016. Furthermore, according to Moore, Schrimpf, and Sushko (2016), FX swap trading rose more in jurisdictions where measures of the underlying FX hedging needs of banks and corporates were the largest and in major currency areas that eased monetary policy further in 2015 and 2016, such as the euro area and Japan.

### *C. Demand for FX hedges vs supply of FX hedges*

Cross-currency investments and funding tend to flow out of currencies where yields and spreads are low and into currencies where yields and spreads are relatively high. Hence, even in the pre-2008 period, when CIP broadly held, there were small negative deviations for EURUSD and USDJPY (because euro area and Japanese nominal yields have been generally lower than US nominal yields), and small positive deviations for AUDUSD (because Australian nominal yields have been generally higher than US nominal yields).

### C.1 Preferred-habitat FX hedgers

Banks and institutional asset managers, who use the cross-currency market to swap out of home currencies (out of USD) to fund long-term USD (home currency) assets, exert negative (positive) pressure on the dollar basis. Corporates can also go through cross-currency markets to swap out of cheap foreign currency funding into the USD and vice-versa. For these types of swap market users, the currency basis represents the cost of putting on a currency hedge. We will refer to these exogenous flows as *FX hedging demand.*

Our measure of FX hedging demand thus draws on three types of preferred-habitat (PH) investors and corporate issuers that constitute maturity clienteles, with the clientele for maturity $\tau$ demanding FX hedges with the same maturity.

**Banks.** We rely on BIS international banking statistics to construct a proxy of FX hedging demand of (select) euro area (Germany, France, Spain, and Italy), Japanese, and Australian banks. Following McGuire and von Peter (2012), we add up the cross-border and local (i.e. vis-a-vis residents of the host country) balance sheet positions reported by banks' home offices and their offices in host countries around the world into a consolidated whole for each banking system.[5].

[Figure 2, about here]

For example, if a Japanese bank uses JPY deposits to fund USD assets, it would typically hedge the associated FX risk using FX swaps. BIS reporting banks' net USD liabilities (the amount that the total on-balance sheet USD assets exceeds the total on-balance sheet USD liabilities, or "funding gap") can be used to proxy for banks' net USD funding or lending in FX swap markets, yielding $y^B_\tau < 0$. By this metric, as of March 2017, off-balance sheet positions of the four euro area banking systems, Japanese banks, and Australian banks stood at minus \$269 billion, minus \$791 billion, and plus \$204 billion, respectively (see Figure 2, top panel). This means that the positioning by Japanese and euro area banks in FX swaps makes the dollar currency basis more negative (e.g. USD more expensive to borrow) in FX swaps, while that of Australian banks exerts an opposite effect.

**Corporate issuers.** We rely on BIS international debt securities statistics to construct the stock of EUR- or JPY-denominated bonds issued by US non-financial corporates (reverse Yankee and Samurai bonds, respectively), and to construct the stock of USD-denominated bonds issued by Australian non-financial corporates (Yankee bonds). The nationality-currency denomination pairing is dictated by the relative levels of corporate yields relative to US. Swapping foreign currency denominated bond funding into the domestic currency creates demand for FX hedges. Following the same convention with respect to USD cross-currency funding as for banks' funding gap, FX hedging demand by corporate issuers can be expressed as follows:

$$
\begin{aligned}
y^C_{\tau,EUR} &= -1 \times 1 \times IDS^\tau_{US,EUR} \\
y^C_{\tau,JPY} &= -1 \times 1 \times IDS^\tau_{US,JPY} \\
y^C_{\tau,USD} &= 1 \times IDS^\tau_{AU,USD}
\end{aligned}
$$

where $EUR$ and $JPY$ denominated outstanding debt issued by US non-financial corporates ($IDS^\tau_{US,EUR}$ and $IDS^\tau_{US,JPY}$) and $USD$ denominated debt issued by Australian non-financial corporates ($IDS^\tau_{AU,USD}$)

[5]Specifically, we rely on a combination of BIS consolidated banking statistics and BIS locational banking statistics to construct total on-balance sheets claims on and liabilities to monetary authorities, banks, and non-banks, denominated in USD, of BIS-reporting banks head-quartered in the euro area (Germany, France, Spain, and Italy), Japan, and Australia; inter-office claims and liabilities are excluded from the calculation.

are multiplied by 1 because we assume a 100% hedge ratio for FX risk. Further, $EUR$ and $JPY$ denominated outstanding debt issued by US non-financial corporates is multiplied by $-1$ to indicate that the associated FX hedging demand consists of borrowing USD (against EUR or JPY) in the swap market, whereas FX hedging by Australian corporates consists of lending USD (against AUD) in the swap market.

As shown in Figure 2, bottom panel, the implied cross-currency position to cover the EUR-denominated reverse Yankee debt of US non-financial corporates has more than doubled since 2014, reaching approximately minus $400 billion. This means that issuers of reverse Yankee bonds needed to borrow $400 billion via currency swaps in order to hedge their EUR-denominated debt liabilities. US corporate issuers of JPY-denominated Samurai bonds also needed to borrow USD in the currency swap markets, but their position is negligible due to low issuance volumes in Japanese corporate bond markets.

**Institutional investors.** For institutional investors, ideally, information on the amount of USD securities in their portfolios along with the FX hedge ratios would yield the total amount of FX hedges associated with their portfolio investment. In practice, we were only able to obtain the necessary data for Japanese institutional investors. The Japanese pension fund industry, following the lead of the Government Pension Investment Funds (GPIF), leaves currency risk on its international bond holdings unhedged. In contrast, Japanese insurance companies, the other major international institutional investor sector, hedge approximately 60-70% of their currency risk (see Barclays (2015a)).

We benchmark Japanese life insurers' low-frequency holdings of foreign currency bonds using the annual reports of the Life Insurance Association of Japan. We then construct the corresponding monthly series using monthly flows from the Japan Ministry of Finance flow data, which reports insurance sector purchases and sales of foreign bonds broken down by residence of the issuer. Finally, we use currency hedge ratios reported by Barclays Research.[6]

[Figure 3, about here]

Since 2014, monthly flows by Japan's life insurers into international long-term debt (predominantly

[6] Annual stock of bond holdings sourced from The Life Insurance Association of Japan (available here); monthly flows applied using data from Japan Ministry of Finance, International Transaction in Securities (based on reports from designated major investors, available here); Japanese life insurance industry average currency risk hedge ratios sourced from Barclays Research (data used in Barclays (2015b) and Barclays (2016))

USD) have often exceeded JPY 500 billion (Figure 3, top panel), or close to $5 billio equivalent. Their position in currency derivatives, $y^I_\tau$, has exceeded $350 billion (Figure 3, bottom panel).

### C.2 Supply of FX hedges ("CIP arbitrage")

Bank FX swap desks that provide FX hedges exert the opposite pressure on the currency basis from that of FX hedgers. Banks may also enter cross-currency markets opportunistically to trade against CIP violations when the basis is wide enough. Central bank deposit facilities have been a popular destination for placing funds by banks that provide USD via FX swaps (see Du, Tepper, and Verdelhan (2018); Bräuning and Ivashina (2016); Rime, Schrimpf, and Syrstad (2017)). Figure 4 shows a close correlation between the quantity of foreign bank holdings of excess reserves ("current account balances") at the Bank of Japan and our measure of FX hedging demand. At its peak, up to one fifth of yen-denominated FX swap proceeds from supplying FX hedges appear to have been parked at the Bank of Japan.

[Figure 4 , about here]

In addition, highly rated supranational and sovereign agencies can effectively engage in CIP arbitrage by raising long-term USD funding to swap for currencies that pay the basis in cross-currency swaps (Du, Tepper, and Verdelhan, 2018). That is, they arbitrage CIP by optimally shifting the currency denomination of their borrowing in response to the basis. Central banks have also been active as arbitrageurs using FX swaps, mostly by lending out their USD reserves. For these users, the currency basis represents a profit opportunity. Hence, such (elastic) flows are more sensitive to price conditions in cross-currency markets, and can be thought of as responding to profit opportunities generated by the exogenous demand for USD forward hedges. We will refer to such flows as *supply of FX hedges*.

Hence, in a similar vein to Vayanos and Vila (2009), FX derivatives markets feature two types of agents: (i) PH investors with specific FX hedging needs (of which there are three sub-types: banks, institutional investors, and corporate bond issuers); and (ii) "arbitrageurs" who provide FX hedges.

## IV. The term structure of currency basis

### A. Short- and long-term currency basis

As shown in Figure 1, above, CIP deviations at the short end can differ from those at the long-end in four ways.[7] First, during crisis periods, particularly following the Lehman Brothers collapse in 2008, the spike in 1-month currency basis was almost an order of magnitude greater than that of 3-year basis. Second, in the post-crisis period starting 2014, the 3-year currency basis has been particularly wide relative to its past levels. Third, as exemplified by the AUDUSD basis, the 1-month basis can turn negative while the 3-year basis remains positive, implying that USD can trade at a premium in FX swaps at the short end while trading at a discount in cross-currency basis swaps at the long-end. Fourth, 3-year CIP deviations have tended to be more persistent, while 1-month deviations are short-lived.

To examine the last point further, Table II shows the results of an augmented Dickey-Fuller (ADF) test for the null hypothesis of a unit root, with tests conducted on time series both at the monthly and daily frequency. The null of a unit root is rejected uniformly for short-term (i.e. 1-week to 6-months) currency basis; however, the ADF test fails to reject the null for maturities of 2 years and above. This is consistent with the above observations that short-term CIP deviations, associated with spikes in short-term FX liquidity costs, tend to be transitory, while longer-term CIP deviations, associated with the pricing of term FX funding and hedging, tend to be persistent.

[Table II and Figure 5 about here]

Figure 5 shows the term structure of CIP deviations (from 1-week to 30-year maturities) for the GFC period, from September to November 2008. During the crisis period, short-term CIP deviations exhibit an "inverted" term structure, all indicating a USD premium in FX swaps at

[7] We obtained the time series of currency basis from Bloomberg data on prices of cross-currency basis swaps, in basis points (bp). For EUR, 6-month tenors are available only as of June 2008 and 3-month tenors are available as of January 2008; for JPY, both 6-month and 3-month tenor become available as of August 2008; for AUD, both 6-month and 3-month tenors become available as of July 2011. For 1-week, 1-month, and 3-month and 6-month tenors, until the basis swap data becomes available for the latter, the cross-currency basis constructed as follows: $\left\{\left(1+\frac{R_{t,\tau}}{100}\right)-\left[\left(1+\frac{R^*_{t,\tau}}{100}\right)\times\left(\frac{F_\tau}{S}\right)^{(360/\tau)}\right]\right\}\times 10000$; where $\tau$ is maturity in the number of days and $F_\tau$ denotes the forward exchange rate of maturity $\tau$ in units of USD per foreign currency. For EUR and JPY, $R_{t,\tau}$ and $R^*_{t,\tau}$ are USD and foreign currency Libor rates of tenor $\tau$ in percentage points, while for AUD $R_{t,\tau}$ and $R^*_{t,\tau}$ are USD and AUD bank deposit rates of tenor $\tau$ because AUD Libor data not available, also expressed in percentage points.

short maturities. For example, the synthetic USD rate for 1-week borrowing implied by EURUSD FX swaps exceeded USD Libor by about 250bp on average from September to November 2008. Therefore, CIP deviations in the crisis period had their origins in significant short-term USD liquidity premia in FX swaps.

[Figure 6, about here]

Figure 6 shows the term structure of CIP deviations in the post-crisis period of January 2014 to May 2018. In contrast to the crisis period, CIP deviations in the post-crisis period are characterized by a U-shaped term structure for currencies against which the USD is trading at a premium (e.g. EUR and JPY) at the longer-end and an inverted U-shaped term structure for currencies against which the USD is trading at a discount (e.g. AUD). This indicates that CIP deviations in this period of calm were driven more by the costs of putting on a longer-term currency hedge than by frictions in funding markets at the short-end. Exceptional periods are quarter- and year-ends, when window dressing around regulatory reporting dates (discussed below) reduces the supply of short-term FX swaps (Figure 6, dashed lines).

### *B. Empirical term structure factors*

This subsection shows the results of a principal component analysis (PCA) to identify the underlying factors driving the term structure of CIP deviations. PCA allows for data-driven selection of the most important latent factors.[8]

[Table III, about here]

Table III shows that the first three orthogonal factors, $F_1$, $F_2$, and $F_3$, explain 98%, 94%, and 86% of the variance of the terms structure of CIP deviations for EURUSD, USDJPY, and AUDUSD, respectively. Most of the variance is explained by the first factor. The results are particularly similar for EUR and JPY, with $F_1$ accounting for 76% and 75% of the variance, respectively, while the first factor for AUD explains 55% of the variance. The share of variance explained by the second factor is similar across all three crosses: 17%, 15%, and 19%. The third factor explains an additional 5% of the variance of EUR and JPY and 11% for AUD.

[8] We follow Wellmann and Truck (2018), see Appendix A.

[Figure 7, about here]

Latent term structure factors tend to capture empirical factors such as level, slope, and curvature (see e.g. inter alia Litterman and Scheinkman (1991), Duffie and Kan (1996) and Dai and Singleton (2000)). Figure 7 shows the time-series of the first two factors for each currency cross along with empirical level and slope factors. The empirical level factor, *CIP Level*, has been calculated by taking the average of the shortest maturity (one week), a medium maturity (3-years) and a long maturity (20 years) basis for each currency pair. The empirical slope factor, *CIP Slope*, has been calculated as the difference between the 20-year and 1-week basis. Indeed, Figure 7, left-panels, show a close relationship between $F_1$ and *CIP Level*, capturing the parallel shift of currency basis at different maturities. Figure 7, right-panels, show a close relationship between $F_2$ and *CIP Slope*, capturing variations in the slope. Particularly for EURUSD and USDJPY, fluctuations in the second factor capture the inversions of the slope of CIP deviations during the GFC, euro area sovereign debt crisis, and around quarter-end and year-end regulatory reporting periods in the implementation phase of Basel III since 2014 (see discussion in Sub-section C.2).

### *C. Economic drivers of CIP term structure*

This subsection relates empirical term structure factors to economic variables. In particular, we show that a) the level of CIP deviations, as proxied by the first factor, is correlated with FX hedging imbalances in each currency against the USD; and that b) the slope of CIP deviations, as proxied by the second factor, is correlated with measures of risk and funding liquidity.

### C.1 Level of CIP deviations and FX hedging imbalances

Given that the level factor explains most of the variation in the term structure of CIP deviations, the strongest economic drivers of the currency basis should exhibit a close association with the level factors, $F_1$'s.

Figure 8 plots $F_1$ for each currency cross against our best estimates of FX hedging demand by banks (red), institutional investors (blue), and corporates (yellow). Even though the data on the stocks of FX hedges are incomplete, the data still exhibit interesting patterns.[9] First, fluctuations

[9] In particular, we lack information on i) euro area and Australian institutional investor FX hedged USD bond holdings and ii) on the hedge ratios of corporate issuers (hence we assume 100% hedge ratio).

in the *level* of CIP deviations, as captured by $F_1$, appear to be linked to fluctuations in FX hedging demand. Second, the sign of $F_1$ appears to be linked to the direction of FX hedging imbalances. Thus, CIP deviations are negative for the cases where the aggregate cross-currency positioning is short USD (e.g. borrow USD via swaps), which is the case of euro- and yen-funded banks, institutional investors, and corporates. And, CIP deviations are positive for the cases where the aggregate cross-currency positioning is long USD (e.g. lend USD via swaps), which is the case of Australian banks and corporates.

[Figure 8, about here]

There is a particularly close association between BIS reporting banks' USD "funding gap" and levels of CIP deviations. This is because banks play a dual role in FX swap markets. On the one hand, they make markets in FX derivatives and take advantage of CIP violations. On the other hand, they also use FX derivatives to hedge currency mismatches on their balance sheets. For example, in EUR and JPY, banks' funding of USD assets reinforces pressure on the basis. This is because, at the consolidated level, these banks need to borrow dollar using FX derivatives just like euro area or Japanese non-bank swap market participants. In contrast, Australian banks raise USD by issuing dollar debt and then swap this funding to AUD to fund domestic currency mortgages.[10] Thus, Australian banks have plenty of USD to lend via swaps to AUD-funded institutional investors, thereby keeping synthetic USD rates below USD Libor rates. As a result, in contrast to EURUSD or USDJPY, USD is relatively cheap compared to AUD in AUDUSD swap markets and the CIP deviations are positive (apart from the GFC period, discussed above).

If CIP violations represented a risk-free arbitrage opportunity, as textbooks would claim, then prices (e.g. CIP deviations) should not respond to quantities (e.g. FX hedging imbalances) in the way they do in Figure 8, because arbitrage capital would flow in to close any incipient CIP deviations. Furthermore, the association of both the sign and size of CIP deviations with FX hedging imbalances speaks against a notion of the existence of fixed no-arbitrage bounds (for example, due to transaction costs). In Sections VI and VII we propose, and test for, the exact economic risks that give rise to balance sheet frictions that, in aggregate, link prices (i.e. CIP deviations) to quantities (i.e. FX hedging demand) in the FX/cross-currency swap markets.

[10] Bertaut, Tabova, and Wong (2013) document that Australian, as well as Canadian, banks have been able to sustain robust issuance of high-grade USD bonds.

### C.2 Slope of CIP deviations and the transient inversion of the term structure

The remaining drivers, orthogonal to those determining the *level* factor of CIP deviations, $F_1$, should thus exhibit a close correlation with the *slope* factor of CIP deviations, $F_2$.

Spikes in the slope factor of CIP deviations capture the inversion of the term structure of currency basis, which have occurred when dislocations in markets for short-term FX swaps were more acute than those in markets for longer terms cross-currency basis swaps, in times of crisis (see Figure 5) and around regulatory reporting dates post-crisis (see Du, Tepper, and Verdelhan (2018) and Figure 6).

[Figures 9 and 10, about here]

Empirical evidence points to three main causes behind such sharp periodic deterioration in EURUSD and USDJPY FX swap market liquidity: spillovers from repo markets, leverage ratio regulation, and window dressing by G-SIB dealers.

**Spillovers from repo markets**. Figure 9 shows that the steepening of the slope factor is closely associated with the widening of short-term (e.g. $<$ 1-month) CIP deviations. This, in turn, is associated with downward spikes in repo spreads, an abnormal situation characterised by negative repo rates, indicating that cash lender in a repo had to pay a premium (and cash borrower in a repo actually earning a positive interest rate). The periodicity around quarter end and year ends reflects the timing of reporting financial statements and regulatory ratios as required by some authorities in their implementation of the Basel standards. Specifically, as of January 2015, international banks have been required to publicly disclose their leverage ratio.[11] This incentivized euro area and Japanese banks to refrain from entering repo transactions at quarter-ends, when their exposure under the Basel III leverage ratio is calculated (CGFS, 2017). However, this has been taking place just as market participants have been looking to enter reverse repo transactions to place their abundant EUR and JPY liquidity in exchange for collateral. The withdrawal of counterparties in repo markets around regulatory periods combined with abundant EUR and JPY liquidity has resulted in the steep discount for EUR and JPY cash in repo markets (i.e. negative repo rates, Figure 9, red lines). As a result, it has become more expensive to place EUR and JPY

[11] Although, the leverage ratio only became a mandatory part of the Basel III Pillar 1 requirements in January 2018 after a period of monitoring and financial calibration.

cash in a repo.

FX swaps are a substitute instrument to repo in that they allow market participants to place EUR or JPY cash for a specified term in exchange for collateral denominated in USD rather than home currency. Consequently, developments in EUR and JPY repo markets spill over to FX swap markets, illustrated in Figure 9 for 1-month tenors and Figure 10 for 1-week tenors.

To make this point more concrete, Table IV compares FX swap-implied basis calculated using Libor rates with those calculated using GC repo rates, for maturities of 1-week, 1-month, and 3-month. For each tenor, we express the resulting difference in the currency basis as a percentage of CIP deviations computed using repo rates as well as in basis points. As the table shows, there is a significant difference when CIP deviations are calculated using repo rates, particularly for short tenors (e.g. 1-week) and particularly for EURUSD. For example, whilst the widest EURUSD 1-week Libor basis reached -836 basis points (*bp*), the corresponding repo basis was only -261*bp*, implying that the forward points (FX forward minus the spot rate) were more closely tied to the pricing in repo markets than in unsecured interbank markets. The difference, both in absolute and in relative magnitudes, between Libor- and repo-basis shrinks as maturities are increased to 1-month and to 3-month. In fact, for USDJPY, the difference in 3-month basis sometimes goes in the opposite direction, meaning that at those maturities the pricing of FX swaps has been more aligned with Libor than with repo rates. Overall, the summary statistics shown in Table IV suggest that for very short tenors, a substantial portion of CIP deviations, computed in a conventional way using Libor rates, can be explained by the developments in the respective repo markets.

[Table IV, about here]

**Leverage ratio regulation**. Cenedese, Della Corte, and Wang (2018) provide evidence that the quarter-end widening of 1-week and 1-month CIP deviations and the decline in corresponding trading volumes are associated with higher leverage ratios of FX swap dealers in the previous quarter. The authors attribute this to the impact of the window dressing of exposures under the leverage ratio by bank dealers. However, what is important to note is that unlike repos, which are on-balance sheet items, FX swaps are treated as off balance sheet in regulatory accounting. As a result, their contribution to exposure under the leverage ratio is extremely small. For instance, the so-called ‘add-on factor’ for potential future exposure under the leverage ratio for FX and gold derivatives of maturities less than or equal to one year is 1% (BCBS, 2014).[12] This means that only 1% of the banks' FX forward positions counts towards the exposure calculation under the leverage ratio. The existing literature has neglected this important fact and has thus misattributed quarter-end dynamics in FX swap markets to the impact of leverage regulation on CIP arbitrage. For instance, Du, Tepper, and Verdelhan (2018) suggest that banks would face a 30$bp$ hurdle rate (a minimum CIP deviations of 30$bp$) to engage in CIP arbitrage if their capital requirement is 3% and return on capital target is 10% ($0.03 \times 0.1 = 0.003$ or 30$bp$). However, given the distinction between on- and off-balance sheet items under BCBS (2014), capital requirements would apply on only 1% of the FX swap position whilst currency basis would be earned on 100% of the position. Hence, for a 1-year position, these assumptions would only imply a (hundred times lower) 0.3$bp$ hurdle rate for CIP arbitrage, or approximately none at all. As such, we think that any direct effects of leverage regulation on activity in FX swap markets should be relatively minor.

**Balance sheet window dressing by G-SIB dealers**. In contrast to leverage ratio regulations, G-SIB scores (specifically the complexity score) take the entire notional amount of off-balance sheet derivatives into account (BCBS, 2013). Whether a G-SIB's capital requirements change in the following year depends on it's G-SIB scores based on the previous year-end exposures. This gives G-SIBs an incentive to reduce their exposure to FX swaps, along with other instruments, on days when the relevant balance sheet metrics are reported. Figures 9 and 10 show the sharp widening of 1-month and 1-week CIP deviations in December 2016 and December 2017, respectively. Krohn and Sushko (2017) draw on high-frequency intraday price and activity data in FX swap markets to provide evidence that window-dressing by G-SIB bank dealers is a significant driver of FX swap market liquidity conditions and 1-month CIP deviations around the balance sheet reporting days.

## V. Empirical analysis

The factor analysis above suggests that one factor drives the persistent level of CIP deviations while another drives short-run fluctuations in CIP deviations. Furthermore, the drivers of the long-run level of CIP deviations appear related to the demand for FX hedges, while the drivers of the short-run spikes around the more persistent level are related to measures of risk and liquidity.

[12] Another component of exposure is the replacement cost (e.g. market value) of an FX swap, but this is negligible for 1-month or 1-week swaps shown here.

This section tests for the significance of the long-run and short-run drivers using an Error Correction Model (ECM). The main dependent variable is the empirical $CIP\ Level$ factor for each currency pair, while the actual cross-currency basis (3-year maturity) is used as a robustness check.

### A. *Data and variables*

Table I lists the explanatory variables. For each currency pair, FX hedging demand ($y_t$) is measured as the implied cross-currency position of BIS-reporting banks ($y_t^B$), non-financial corporates' cross-currency debt securities liabilities ($y_t^C$), and, for USDJPY, also institutional holdings of USD-denominated bonds hedged for currency risk ($y_t^I$).

Risk is proxied by euro area, Japan, and Australia banks' CDS spreads, or, alternatively, with the VIX index. Our benchmark measure of funding liquidity follows Mancini Griffoli and Ranaldo (2012) and captures rollover risk of unsecured funding as the 1-week to 1-month OIS spread in USD relative to that in EUR, JPY, or AUD ($OIS\ roll_t$). Alternative measures of funding liquidity considered for robustness are bank deposit rate-OIS differentials in the relevant currency pairs ($Deposit_t - OIS_t$) and GC Repo-OIS spread differentials between the relevant currency pairs ($Repo_t - OIS_t$). All interest rate maturities are 1-month.

Accounting for repo or deposit spreads in different currencies is important because differences in liquidity premia across the respective currencies have been driving short-term CIP deviations in the post-2014 period, as emphasized by Rime, Schrimpf, and Syrstad (2017). A negative value of the USD GC repo spread differential indicates that USD collateral (cash) is more expensive (cheaper) than foreign currency collateral (cash). This was the case during the GFC when funding markets were hit by massive US Treasury collateral shortages (see Hoerdahl and King, 2008). More recently, excess liquidity in EUR or JPY implies an excess supply of cash (excess demand for collateral) to be placed (sourced) via EUR or JPY repo. This led to negative repo spreads in EUR or JPY (i.e. compensation for receiving cash).

Finally, we chose proxies for market liquidity following a similar approach to Mancini Griffoli and Ranaldo (2012). We measure FX market liquidity using currency bid-ask spreads ($FX\ bid - ask_t$, for each currency pair) and money market liquidity using the first principal component of 1-month OIS bid-ask spreads in the four currencies ($OISLiq_t$).

[Table I, about here]

### B. Error-correction model specification

As noted in the previous section, unit root test results tend to fail to reject the null of a unit root for longer maturity (eg 2-years and up) CIP deviations (see Table II, above). Given that the time-series of $F_1$ from the PCA analysis of the term structure as well as of the empirical *CIP Level* factor are similar to longer-term cross currency basis, we test all three variables for cointegration with $log(y_t)$, the (log of) FX hedging demand. Since there is some uncertainty as to whether the series are I(0) or I(1), we use the auto-regressive distributive lag (ARDL) bounds test for cointegration, developed by Pesaran, Shin, and Smith (2001). The ARDL bounds test allows for breaks in the I(1) process and for testing for cointegration among time-series falling between I(0) and I(1). Table V shows the results. If we also include the years 2006 and 2007 into the sample period, 7 out of 9 combinations across three different pairing and thee currency crosses exhibit cointegration (top panel). Limiting the sample to 2008 onwards produces statistically significant results for all 9 combinations.

[Table V, about here]

Next, for each currency cross, we test for Granger-causality between $F_1$, the empirical $CIP\ Level$ factor, or the actual 3-year currency basis ($b_{3y,t}$) with FX hedging demand ($log(y_t)$). The results shown in Table VI indicate that at FX hedging demand tends to Granger-cause the measures of CIP deviations, but not the other way around.

[Table VI, about here]

On the basis of the co-integration and Granger-causality tests, we formulate the following ECM with the *level* of CIP deviations as dependent variables.

$$\begin{aligned} \Delta CIP\ Level_t &= \alpha_0 + \phi \hat{z}_{t-1} + \alpha_y \Delta log(y_{t-1}) + \sum \alpha_j X_{j,t} + \sum \alpha_i \Delta CIP\ Level_{t-1} + \epsilon_t \\ CIP\ Level_t &= \beta_0 + \beta_y log(y_t) + z_t, \end{aligned} \tag{2}$$

where $CIP\ Level$ denotes the empirical level factor of CIP deviations, $\hat{z}$ is the residual from the long-run cointegrating equation, and $X_j$ is the vector of additional drivers of short-run changes in the level of CIP deviations, including variables relating to risk, funding liquidity, and market liquidity.

The results of the term structure analysis are stated more formally in the following propositions and in the associated predictions (i) through (v) for the ECM estimation results.

**Proposition 1.** *FX hedging demand & the level of CIP deviations.* If $y_\tau > 0$ then $CIP\ Level > 0$, if $y_\tau < 0$ then $CIP\ Level < 0$, and $CIP\ Level \propto y_\tau$. The sign of currency basis depends on the sign of FX hedging imbalances, and the magnitude of currency basis depends on the size of FX hedging imbalances.

(i) FX hedging demand drives the long-run *level* of CIP deviations: $\hat{\beta}_y \neq 0$.

(ii) The more net short (long) the FX hedging demand for USD, the more negative (positive) the *level* of CIP deviations: $\hat{\beta}_y > 0$.

**Proposition 2.** *Temporary dislocations due to credit risk & illiquidity.* Dislocations in bank credit risk and money market liquidity conditions cause temporary spikes in CIP deviations (due to inversion in the slope of CIP deviation as short-term currency basis widen) that are subsequently reversed.

(iii) If the level of CIP deviations is too wide given the level of FX hedging demand, then CIP deviations narrow in the subsequent month: $\hat{\phi} < 0$.

(iv) Short-run changes in CIP deviations are not caused by short-run fluctuations in FX hedging demand: $\hat{\alpha}_y = 0$.

(v) Short-run changes in CIP deviations are caused by market, credit, or liquidity risk: $\hat{\alpha}_j \neq 0$ at least for some $j$.

### *C. Estimation results*

Table VII shows the baseline ECM estimation results. Focusing on the long-run co-integration equations (bottom panel), the estimated coefficients $\hat{\beta}_y$'s on the log of FX hedging demand ($log(y_t)$)

are positive and significant for all three currency pairs. This result confirms predictions (i) and (ii) that FX hedging demand drives the long-run *level* of CIP deviations, and the more net short (long) the FX hedging demand for USD, the more negative (positive) the *level* of CIP deviations. The coefficient magnitude is largest for USDJPY, indicating that a 1% increase in the aggregate short USD position via the FX hedges by Japanese banks, Japanese insurance companies, and US corporate issuers of samurai bonds is associated with a 3.5*bp* wider level of CIP deviations.

[Table VII, about here]

Next, turning to the short-term error-correction equation, the coefficients $\hat{\phi}$'s on the lagged residual from the co-integration equation ($\hat{z}_{t-1}$) are negative and statistically significant for all three currency pairs. This confirms prediction (iii) that if the *level* of CIP deviations is too wide given the level of FX hedging demand, then CIP deviations narrow in the subsequent month. More specifically, negative estimates of $\hat{\phi}$'s for EURUSD and USDJPY indicate that if the level of CIP deviations was too negative (wide) in period $t-1$ given the level of FX hedging demand $y_{t-1}$ (residual $\hat{z}_{t-1} < 0$), then CIP deviations become less negative (narrow) in period $t$ ($\Delta CIP\ Level_t > 0$). The converse interpretation applies for the case of AUDUSD, where both the level of CIP deviations and USD positioning via FX hedges have been positive. For example, the coefficient estimate on $\hat{z}_{t-1}$ of -0.1 in column (1) for EURUSD indicates that if the $t-1$ *level* of CIP deviations was 1*bp* more negative (wider) than stipulated by its long-run relationship with the level of FX hedging demand, then in the subsequent period $t$ the *level* of CIP deviations will correct (narrow) by 0.1*bp*. This result is strongest for AUDUSD, where more than a third of the overshooting corrects within the next month: $\hat{\phi}$=-0.32 in AUDUSD column (1) and $\hat{\phi}$=-0.37 in AUDUSD column (2).

The coefficients $\hat{\beta}_y$'s on lagged changes in FX hedging demand ($\Delta log(y_{t-1})$) are not significant. This confirms prediction (iv) that short-run changes in CIP deviations are not caused by short-run fluctuations in FX hedging demand.

The coefficient estimates on risk (whether measured by banking sector credit risk, $\Delta CDS_t$ or aggregate market risk, $log(VIX_t)$), are negative and significant for all three currency pairs, indicating the USD funding premium via cross-currency derivatives rises when market volatility rises or the credit worthiness of foreign banks deteriorates. The coefficients on funding liquidity, as measured by differences in roll-over risk of unsecured funding in USD versus EUR, JPY, or AUD money markets ($OIS\ roll_t$), are also negative and significant. These results confirm prediction (v) that short-run changes in CIP deviations are caused by market, credit, and liquidity risk.[13]

## VI. Theoretical framework for the balance sheet constraint

Our empirical analysis points to a balance sheet constraint that links fluctuations in FX hedging demand to fluctuations in CIP deviations. In this section, we model the empirical results through the lens of preferred-habitat limits to arbitrage in which counterparty and market risks of OTC FX swaps give rise to balance sheet costs that prevent CIP from holding. By market clearing, the balance sheet exposure of those taking advantage of CIP violations is exactly equal to net FX hedging demand.

**Supply of FX hedges.** Suppose agents trading against CIP violations are risk-averse, have an exponential utility function, $-\mathbb{E}_t[\exp(-\rho(\mathrm{d}W_t))]$, and choose the amount of dollars to supply via FX swaps with maturity $\tau$, $x_{t,\tau}$, so as to maximize utility from wealth at each time $t$ where wealth evolves according to

$$\begin{aligned} \mathrm{d}W_t \;&=\; \left(W_t - \int_0^T x_{t,\tau}\mathrm{d}\tau\right) r_{t,\tau}\mathrm{d}t \\ &+\; \left(\int_0^T (1-\theta_{t,\tau})x_{t,\tau}(f_{t,\tau} - s_t + r^*_{t,\tau})\mathrm{d}\tau\right)\mathrm{d}t \\ &+\; \left(\int_0^T \theta_{t,\tau}x_{t,\tau}\left(\mathbb{E}_t[\mathrm{d}s_t] + r^*_{t,\tau}\right)\mathrm{d}\tau\right)\mathrm{d}t \end{aligned} \tag{3}$$

with the assumption

$$\mathbb{E}_t[\mathrm{d}s_t] \sim N(f_{t,\tau} - s_t, \sigma^2_{t,\tau}). \tag{4}$$

The bond spot rates, $r_{t,\tau}$ and $r^*_{t,\tau}$, and the currency forward rate, $f_{t,\tau}$, are both known at time

[13] Since the variable $CIP\ Level_t$ is a statistical construct that takes the averages of CIP deviations across several maturities, we also check the robustness of the results to using the actual currency basis from prices of cross-currency basis swaps (we pick 3-year maturity) as the dependent variable. Appendix Table B1 shows that the results are qualitatively robust. At the same time, quantitatively, the level effects of FX hedging demand on 3-year basis is much greater than it is on the average, as are the error correction coefficients on the measures of risk and funding liquidity (except for AUDUSD for the latter). One explanation for this is that the $CIP\ Level_t$, considered previously, also includes the level of short-term (e.g. 3-month) basis, whereas the term-structure analysis indicates that FX hedging imbalances exhibit the closest association with long-term (eg 3-year) CIP deviations (see Section IV). Finally, Appendix Table B2 shows that the results are also robust to using alternative funding liquidity proxies, namely interbank deposit-, $Deposit_t - OIS_t$, and repo-, $Repo_t - OIS_t$, spread differentials, where $Repo_t - OIS_t$ is interacted with post-2014 dummy for the reasons described in Sub-section C.

$t$; however, there is still uncertainty stemming from counterparty risk in the swap. The risk of counterparty default to pay back the dollars at the forward rate introduces a (small) probability at each time-$t$, $\theta_{t,\tau}$, that FX collateral would have to be exchanged back into dollars at time-$\tau$ at the prevailing (ex-ante unknown) exchange rate. Substituting Equation (3) into the utility function and assuming exchange rate returns are log-normally distributed (Equation (4)) allows us to rely on standard properties of CARA-normal optimization (see Appendix B).

**Market clearing forward rate.** Imposing that markets clear such that $x_{t,\tau} = y_{t,\tau}$ with

$$y_{t,\tau} = y^B_{t,\tau} + y^I_{t,\tau} + y^C_{t,\tau}, \tag{5}$$

the sum of demand for FX swaps across PH-investors, and maximizing the certainty-equivalent with respect to $x_{t,\tau}$ yields the market clearing forward rate,

$$f_{t,\tau} = s_t + r_t - r^*_t + \int_0^T \rho\sigma^2_{t,\tau}\theta_{t,\tau}y_{t,\tau}\mathrm{d}\tau. \tag{6}$$

Equation (6) effectively says that for CIP to hold, the last term must be zero.[14] Instead, if counterparty risk of exposure to OTC FX derivatives is recognized, $\theta_{t,\tau} > 0$ (no matter how small), as stipulated by Equation 3, then its interaction with market risk $\sigma^2_{t,\tau}$ and risk aversion (inverse of balance sheet risk tolerance), $\rho$, adds a mark-up proportional to FX hedging imbalances, $y_{t,\tau}$, to the forward exchange rate, $f_{t,\tau}$. The amount by which the FX forward rate deviates from that implied by CIP is then exactly the currency basis. Hence, basic theory suggests that frictions specific to OTC FX derivatives markets contribute significantly to the persistent CIP deviations associated with FX hedging imbalances.

## VII. Validation of the constraint

In the previous section we have shown that trading against CIP violations incurs exposure to OTC FX derivatives and so gives rise to FX collateral risk. The costs of provisioning for this risk is proportional to the size of the exposure taken onto balance sheets so that markets for FX hedges clear. Hence, we have shown that, in aggregate, CIP deviations arise because forward exchange

[14] Note that equation (6) can be re-written as $b_{t,\tau} = \int_0^T \rho\sigma^2_{t,\tau}\theta_{t,\tau}y_{t,\tau}\mathrm{d}\tau$.

rates include a mark-up for FX collateral risk, which is proportional to FX hedging demand. Specifically, the elasticity with which changes in FX hedging demand affect premia in forward exchange rates, and hence CIP deviations, depends on how large the interaction of counterparty and market risk is.

### A. *Basis elasticity to FX hedging demand & the risk factors*

We estimate the elasticity of currency basis to FX hedging demand by running a Kalman filter regression of equation (6). Hence, we estimate the following the state space representation of a time-varying parameter model:

$$b_{t,3} = [\log(y_t)]' \beta_t + e_t, \quad e_t \sim N(0,R) \tag{7}$$

$$\beta_t = c + F\beta_{t-1} + \nu_t, \quad \nu_t \sim N(0,Q) \tag{8}$$

where $b_{t,3}$ is the 3-year currency basis for each currency; $[\log(y_t)]$ is a $1 \times k$ vector of the logarithm of net FX hedging demand at time $t$; $e_t$ and $\nu_t$ are independent errors; $\beta_t$ is a $k \times 1$ vector of time-varying parameters; $F$ is a $k \times k$ diagonal matrix with diagonal elements $|f_{i,i}| < 1$; $R$ is the variance of $e_t$; and $Q$ is the $k \times k$ covariance matrix of $\nu_t$ (see Appendix C for further details on methodology).

**Proposition 3.** *Structural premia for counterparty & market risk* $\partial b_{t,\tau}/\partial y_{t,\tau} = \partial f_{t,\tau}/\partial y_{t,\tau} = (\rho\sigma^2_{t,\tau} \times \theta_{t,\tau})$. The elasticity with which FX hedging imbalances affect the level of CIP deviations equals the elasticity with which FX hedging imbalances affects forward exchange rates (implicit in the pricing of FX swaps and cross-currency swaps), which is proportional to FX collateral risk. This can be re-stated as the following prediction of time-varying parameter estimation results:

(vi) $\beta_t \propto (\rho\sigma^2_{t,\tau} \times \theta_{t,\tau})$. Time-varying regression coefficient of currency basis on the (log of) FX hedging demand captures marginal cost of FX collateral risk and is proportional to the product of FX option-implied (risk-neutral expected) volatility and bank credit spreads.

[Figure 11 and Table VIII, about here]

Figure 11 plots the changes in the estimated $\beta_t$'s against the interaction between the logarithm of 3-year FX option implied volatilities and banking sector CDS spreads, $\rho\sigma^2_{t,\tau} \times \theta_{t,\tau}$. The figure shows close correlation between $\beta_t$'s and $\rho\sigma^2_{t,\tau} \times \theta_{t,\tau}$ for each currency pair. The relationship emerged during the GFC and has not gone away since, suggesting a structural changes in the way in which ups and downs in FX hedging demand affect the pricing of FX derivatives and, hence, CIP deviations, in the post-GFC period.

Table VIII shows the results of the error-correction equation of the 3-year currency basis re-estimated using the residual from the cointegrating equation estimated using Kalman filter. The coefficients on $\hat{z}_{t-1}$ are negative and statistically significant, indicating a good fit and error correction of 3-year currency basis back to the long-run level determined by the level of FX hedging demand in each currency. The coefficients on other variables are also in line with the baseline ECM specifications (see Table VII through B2).

### B. *Relationship to regulation and risk management*

Textbooks describe CIP arbitrage as a self-financing strategy with exchange rate risk fully hedged. In such a setting, demand shocks have no impact on prices because demand shocks are offset by arbitrage, with the latter being profitable up to the point at which CIP is restored. This is depicted by the horizontal supply curve of FX hedges in Figure 12. Specifically, prior to the GFC, the supply of FX hedges was very elastic because the standard practice in the industry was to mark derivatives portfolios to market without taking the counterparty's credit quality into account (Zhu and Pykhtin (2007)). This ensured that CIP as a no-arbitrage conditions held apart from short periods when the balance sheets of CIP arbitrageurs themselves were impaired.

[Figure 12, about here]

However, since the GFC experience, neither the banks (in their $P\&L$ calculations) nor the regulators treat cross-currency positions as riskless. Particularly post-GFC, prudent risk management requires financial institutions to account for potential losses on their off-balance sheet exposures to derivatives such as currency swaps.[15] In FX derivatives, this means that market risk and counterparty risk are priced in at all times, even when measured risks are low.[16] Indeed, industry reports

[15]See, for example, EBA (2015) and BCBS (2015b).

[16]Consistent with higher post-crisis counterparty risk concerns among traditional FX market participants, Levich (2012) finds that trading in interbank currency forwards has declined in favour of currency futures. Because futures are traded on an exchange and counterparties post margins, they involve significantly lower counterparty risks than forward contracts, which are over-the-counter.

indicate that banks have been applying greater credit charges to swap pricing.[17]

Our theoretical setup captures these changes in a simplified way. The balance sheet costs to trading against CIP violations arise endogenously due to a combination of counterparty and market risk. The difference between the risk-free derivatives portfolio value and the true portfolio value taking the possibility of counterparty default into account is what is known as credit value adjustment (CVA). CVA is essentially equal to the present discounted value of the risk-neutral expectation of the market value of the swap in the event of a counterparty default (see Duffie and Kan (1996) and Andersen, Duffie, and Song (forthcoming)).[18] CVA risk is how off-balance sheet derivatives are accounted for in the broader RWA regulatory requirements (see BCBS (2017)). Banks are now required to have a CVA desk or a similar function, with capital requirements calculated for all covered transactions (BCBS (2015a)). Cenedese, Ranaldo, and Vasios (2018) document persistent OTC premia for interest rate swaps that are not centrally cleared. In particular, their results point at CVA and Capital Valuation Adjustment (KVA) as important drivers of the premia in non-centrally cleared transactions. Consistent with our theoretical setup, these authors also find that swap prices tend to increase with notional amount and remaining time to maturity, because these raise total contract risk. For FX derivatives, virtually none of which are centrally cleared, their findings would imply that dealers pass on regulatory costs of virtually the entire (i.e deliverable) FX derivatives market to market prices. Furthermore, the price implications of such premia are larger in FX and cross currency swaps, because, unlike interest rate swaps, the former require counterparties to exchange principal amounts, implying a significant amount of FX collateral risk.

Prudent risk management requires banks to recognise exposure to these risks with higher capital charges for both credit and market risks, by putting on offsetting hedges (such as buying a CDS on the counterparty), or by posting collateral and exchanging variation margins with their counterparties during the duration of the swap (the process regulated by the so-called Credit Support Annex (CSA)). A two-way CSA significantly reduces, if not eliminates, CVA capital charges: exchanging initial margins reduces counterparty risk (e.g. loss given default captured by CVA) and required capital against the exposure to default risk (KVA). However, it increases other costs related to collateral and funding, known as the Margin Valuation Adjustment (MVA). Indeed, for a few years, counterparties in OTC derivatives transactions have been required to post margins depending on

[17]See, for example, "Small fish big prize: the market markers out to eat the banks' lunch", Euromoney magazine, December 2015.

[18]See also Assefa, Bielecki, Crépey, Jeanblanc, Brigo, and Patras (2009) and Pykhtin (2009).

the riskiness of the counterparty and market volatility so that 100% of collateral is covered (see BCBS (2015a)). Hence, the problem of credit and capital has been largely transformed into that of the funding of margins and collateral. Even if FX hedging imbalances where small, implying small net position on the supply side of FX hedges, FX swap dealers would still incur what is now known as Funding Valuation Adjustment (FVA), according to Andersen, Duffie, and Song (forthcoming), who show that because hedging swap transactions by banks in inter-dealer markets requires them to post collateral, the latter needs to be financed at the expense of shareholders.[19,20] As a result, every dollar of exposure to clear the market for FX hedges carries a cost from earmarking additional capital, buying credit protection, or funding of collateral and margins. Hence, the supply curve of FX hedges has become upward-sloping, as shown in Figure 12. Cross currency basis can become particularly wide if there is an exogenous outward shift in the demand curve for FX hedges, as has been the case because of divergence in relative yields and credit spreads on the back of aggressive, asynchronous, unconventional monetary policies (depicted as $M - policy$ in the diagram) conducted in major currency areas.

## VIII. Conclusion

The failure of CIP for some of the most liquid currency crosses in a period of relatively calm markets runs contrary to the majority of the pre-crisis literature in international finance. We provide robust empirical evidence that our measures of FX hedging demand are first order drivers of the persistent *level* of CIP deviations. The underlying frictions that make CIP deviations respond to changes in FX hedging demand are specific to FX derivatives markets, which are predominantly OTC. The associated premia for the cost of provisioning for market and counterparty risks of FX derivatives exposures, undertaken to clear FX hedging demand, are priced into the forward exchange rates, taking them out of line with CIP. These frictions rise in importance with the maturity of the contracts. Our empirical and theoretical frameworks also explain why USD is expensive to borrow in cross-currency markets against some currencies (i.e. negative CIP deviations) whilst cheap to borrow against other currencies (i.e. positive CIP deviations). The implication is that it is

[19]Based on work in Andersen, Duffie, and Song (forthcoming), Duffie (2018) carefully shows with theory and evidence that bank credit spreads, which as the authors note are widening as a result of big banks being less likely to receive government bailouts, are an effective lower bound on the excess return (above a fair market return) that dealers must earn on (aggregate) trading activities to offset the cost of balance sheet space to legacy shareholders.

[20]Collectively CVA, KVA, MVA, and FVA are known as XVAs.

misleading to look for stable no-arbitrage bounds to explain CIP deviations because the structural relationship between prices and quantities in the FX/cross-currency swap markets implies that the level of CIP deviations is proportional to aggregate FX hedging imbalances, which change over time. Other factors related to money market conditions and quarter-end anomalies are associated with the occasional inversions of the *slope* of CIP deviations across maturities, but are largely orthogonal to the main drivers of the persistent CIP failure in the post-crisis period.

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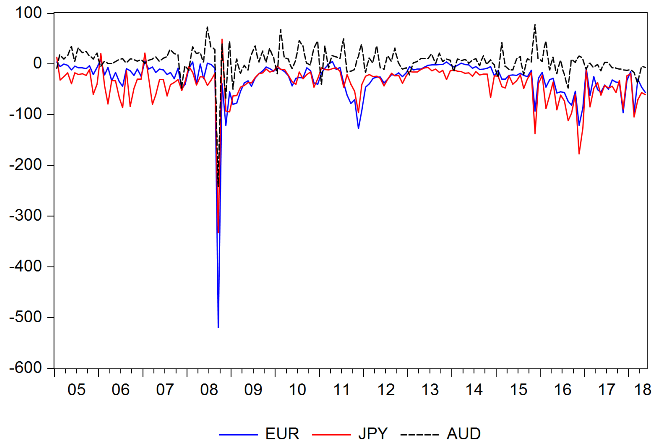
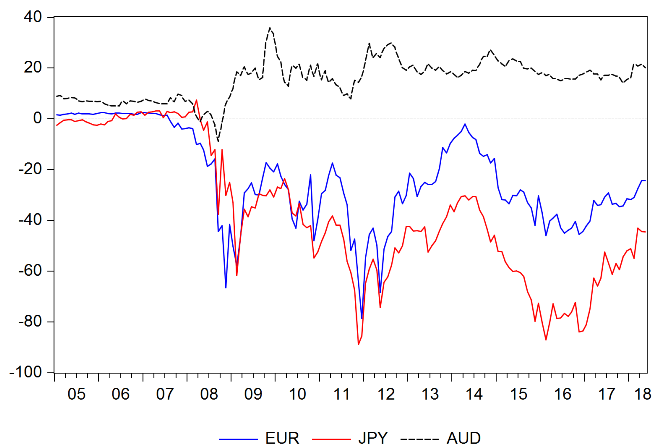
# Figures




(a) 1-month basis: $b_{1m}$




(b) 3-year basis: $b_{3y}$

**Figure 1. Dollar basis for select currency crosses and maturities.**

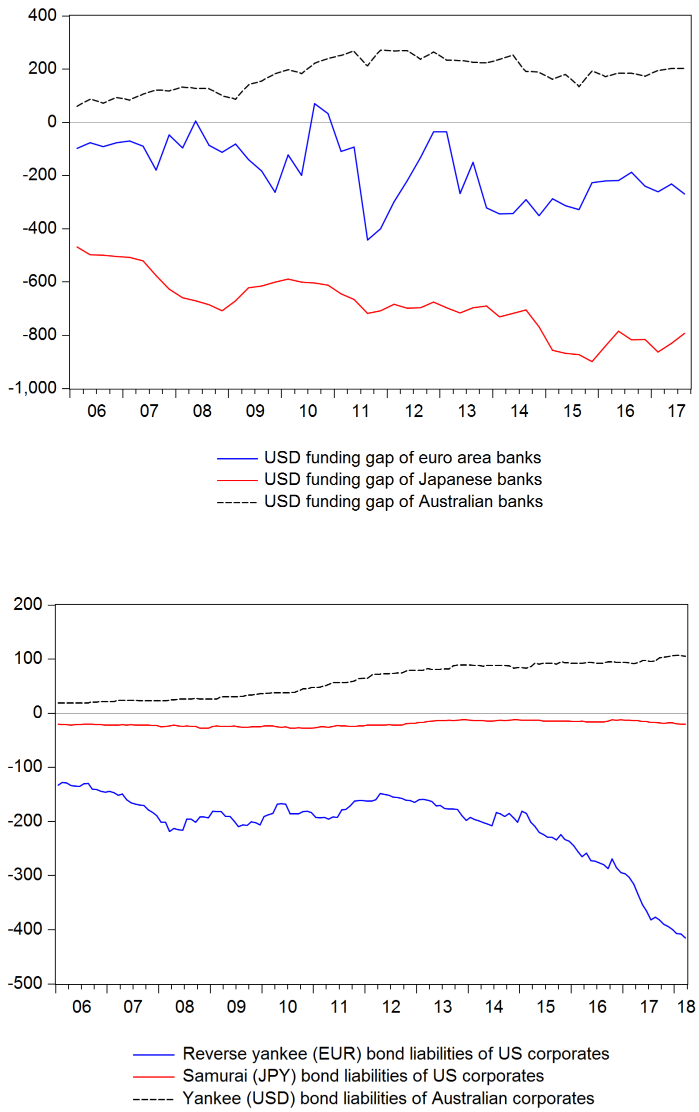



**Figure 2. Cross-currency FX hedging positions in USD vis-a-vis home currencies of banks, $y_\tau^B$, (top) and of non-financial corporate issuers of foreign currency debt, $y_\tau^C$, (bottom); in USD billions.**
Top panel: $y_\tau^B$ equates gross USD on-balance sheet liabilities to gross USD on-balance sheet assets of banks headquartered in respective jurisdictions (*Sources:* BIS Consolidated Banking Statistics (immediate borrower basis) and BIS Locational Banking Statistics (by nationality), see McGuire and von Peter (2012) for details). Bottom panel: $y_\tau^C$ for each respective currency are the amounts outstanding of reverse yankee EUR bond liabilities of US corporates (blue line), Samurai JPY bond liabilities of US corporates (red line) and yankee USD bond liabilities of Australian corporates (dashed black line) (*Source: BIS International Debt Securities Statistics*).

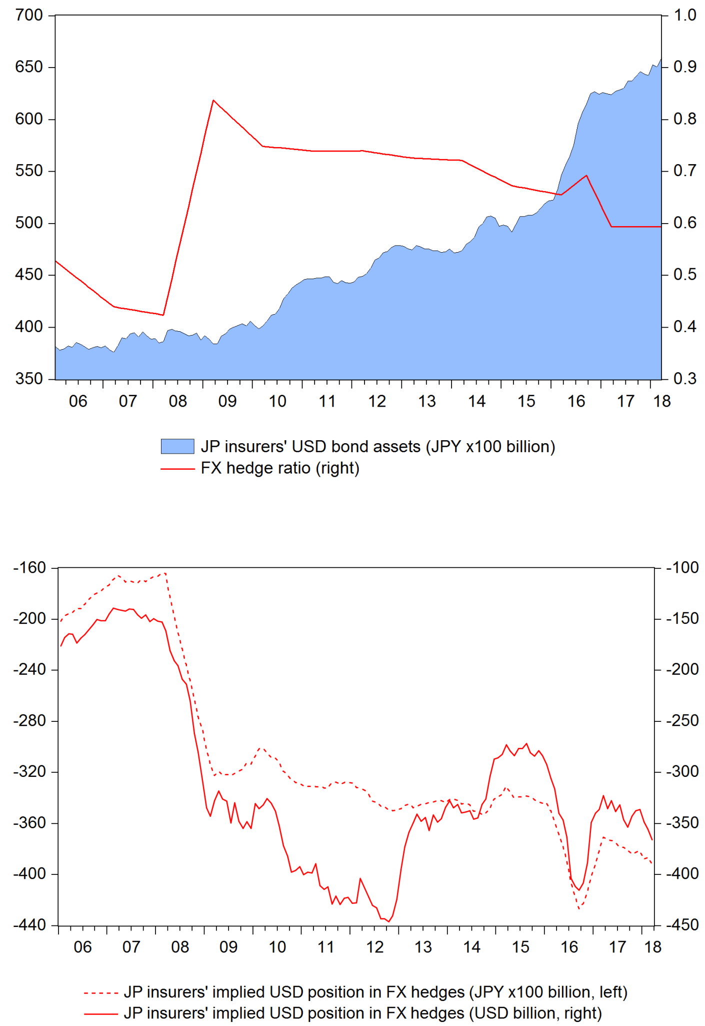



**Figure 3. Cross-currency FX hedging position of Japanese life insurance companies, $y^I_\tau$. Holdings of USD-denominated bonds and time-varying FX hedge ratio (top); the associated implied cross-currency position in FX hedging markets (bottom).**

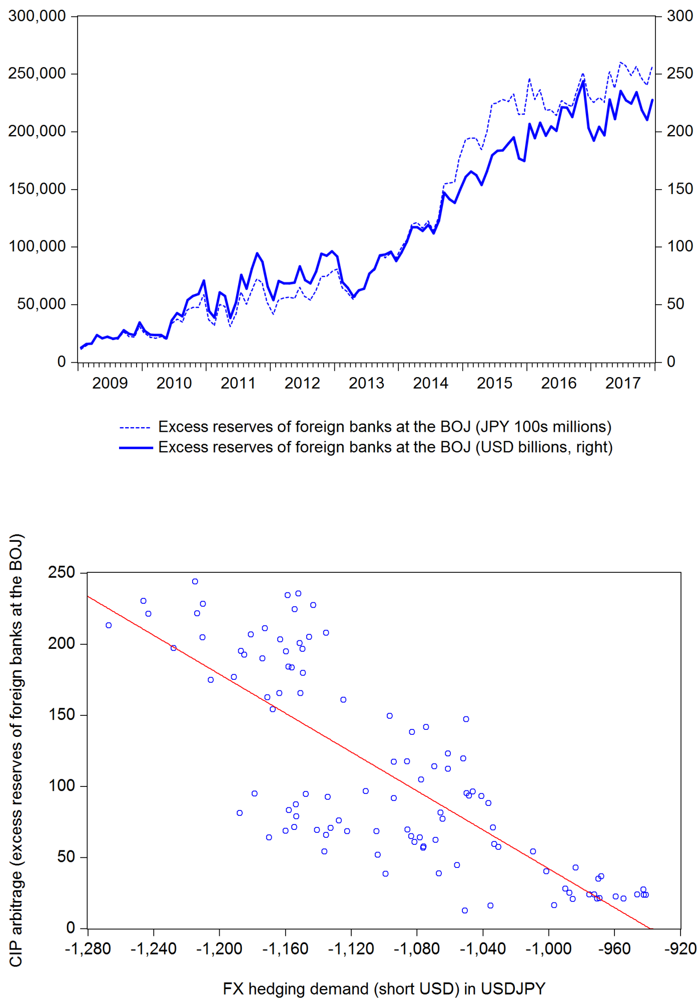
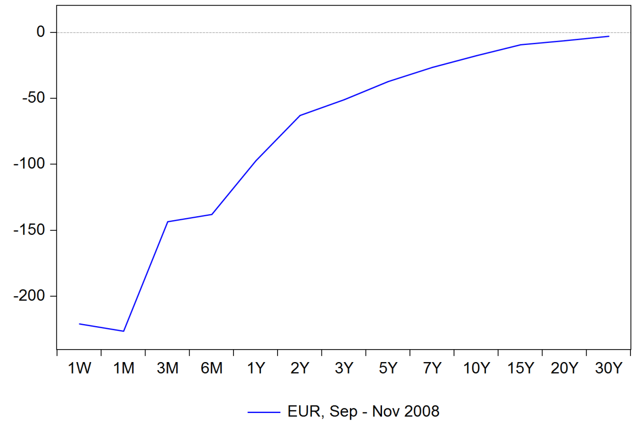
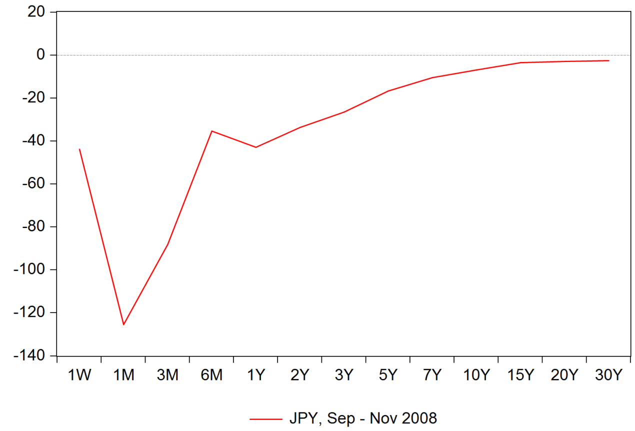


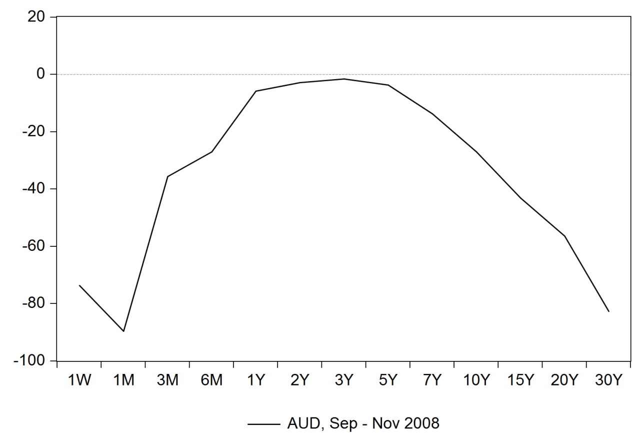

**Figure 4. Proxy for CIP arbitrage: excess current account balances of foreign banks at the Bank of Japan (top); and their correlation with FX hedging demand (bottom).**




(a) EURUSD basis, crisis period

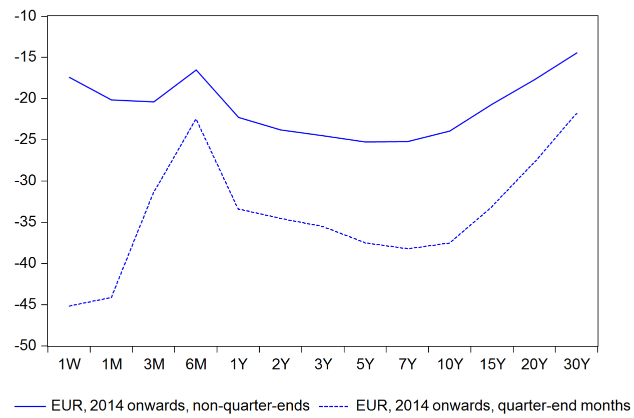



(b) USDJPY basis, crisis period

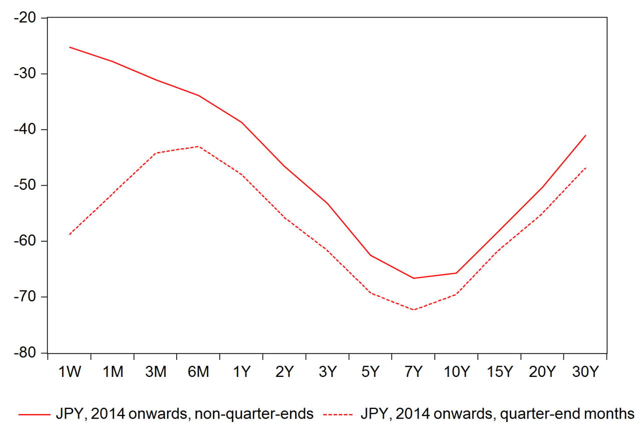



(c) AUDUSD basis, crisis period

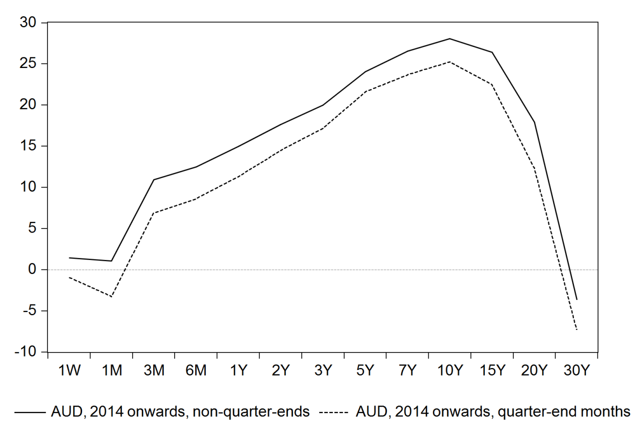
**Figure 5. Average term structure of CIP deviations during a crisis period**. Sample period starts after the collapse of Lehman Brothers: October - November 2008.




(a) EURUSD basis, post-crisis




(b) USDJPY basis, post-crisis




(c) AUDUSD basis, post-crisis

**Figure 6. Average term structure of CIP deviations in the post-crisis period.** Sample period is January 2014 - May 2018; dashed lines indicate the term structure during quarter-end months.

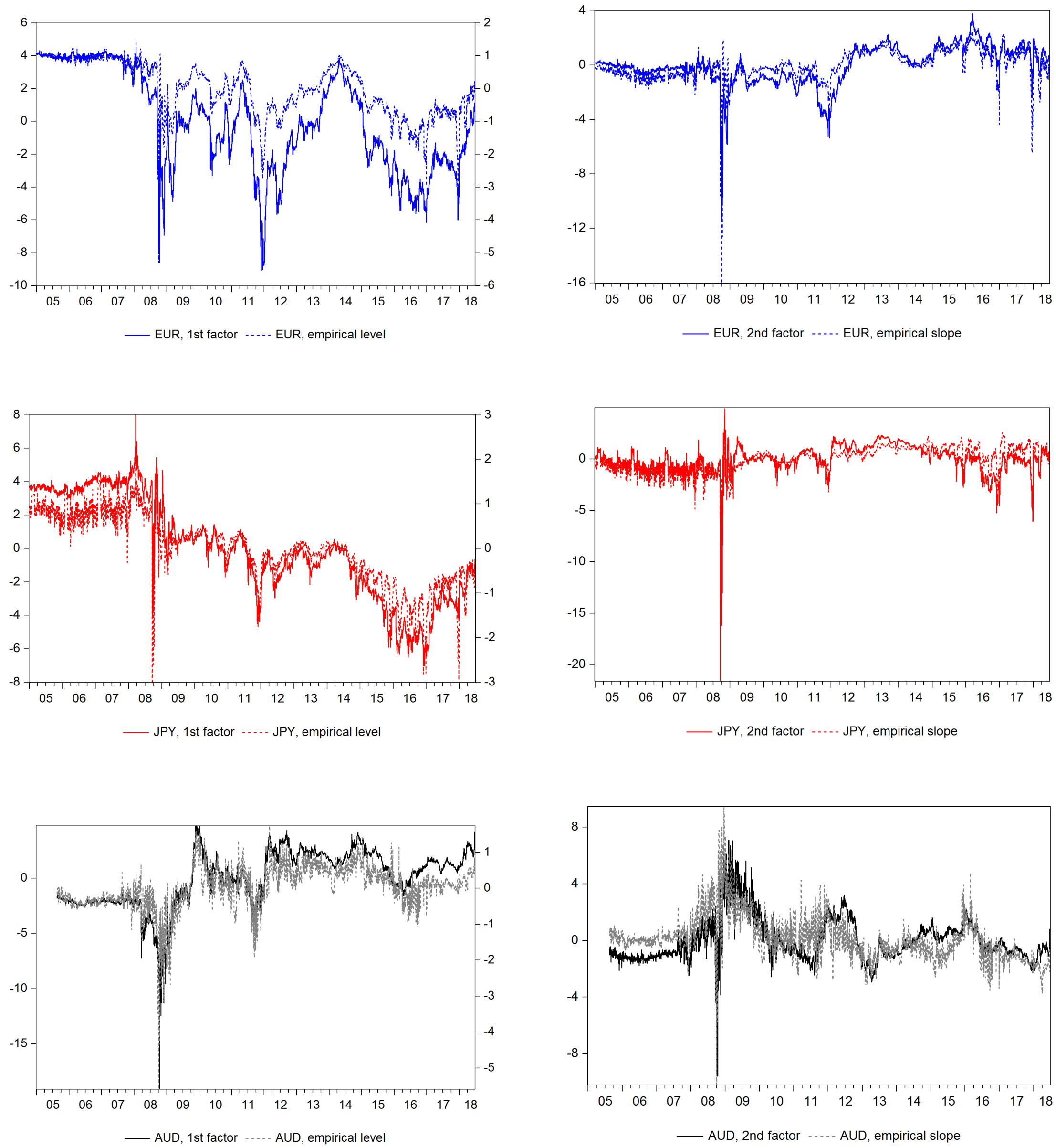



**Figure 7. Estimated and empirical factors.** *Left:* First estimated factor and the empirical *CIP Level* factor. *Right:* Second estimated factor and the empirical *CIP Slope* factor. For each currency cross, the sample consists of 1-month through 30-year currency basis, daily frequency, 01/01/2005 to 25/06/2018. The empirical level factor has been calculated by taking the average of the shortest maturity (one week), a medium maturity (3-years) and a long maturity (20 years) basis for each currency pair. The empirical slope factor has been calculated as the difference between the 20-year and 1-week basis.

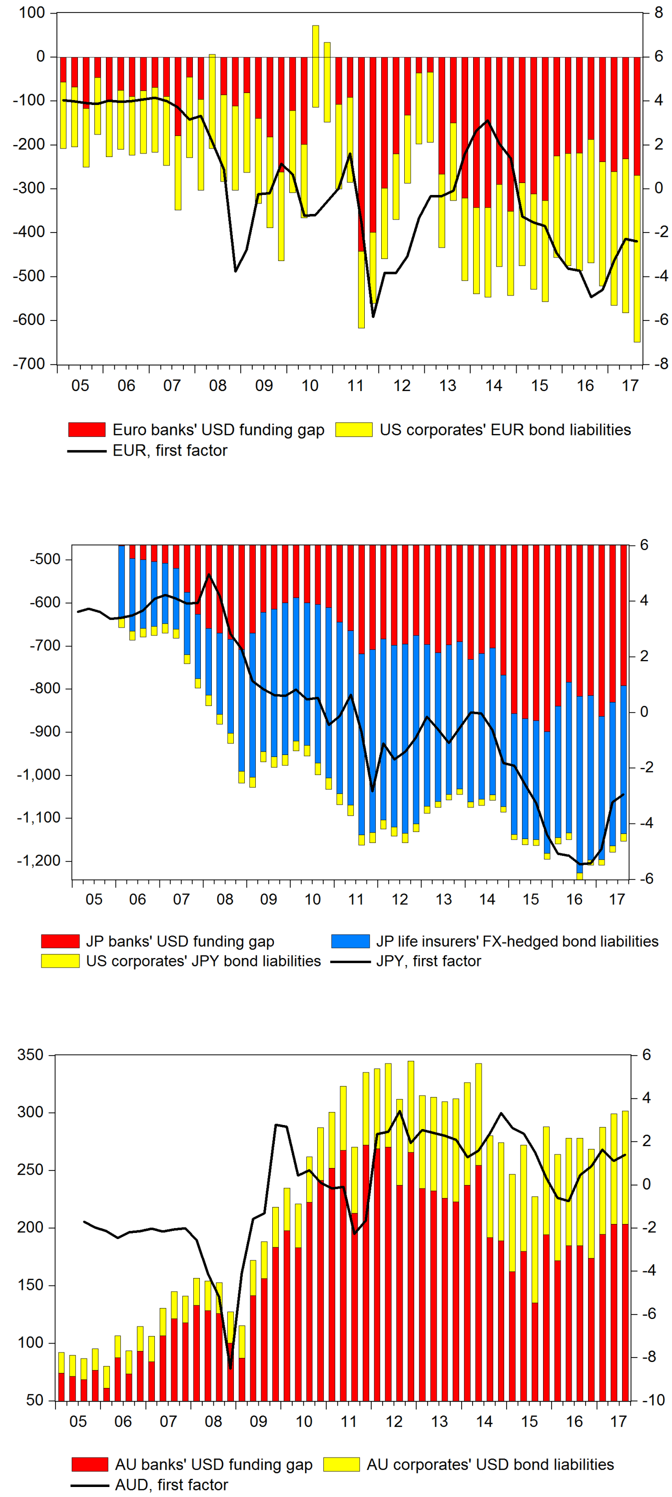



**Figure 8. Estimated and economic factors: first principal components.**

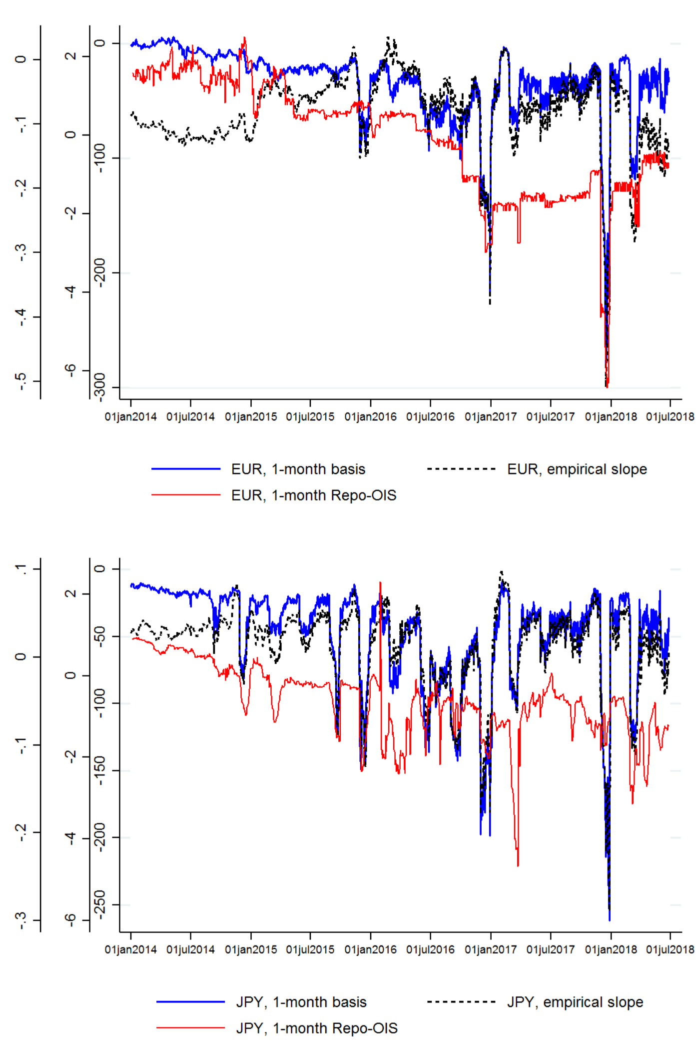



**Figure 9. 1-month CIP deviations, empirical slope factor, and repo market conditions in EUR and JPY.** The sample consists of 1-month currency basis, monthly frequency, 01/01/2014 to 25/06/2018. The empirical slope factor has been calculated as the difference between the 20-year and 1-week basis.

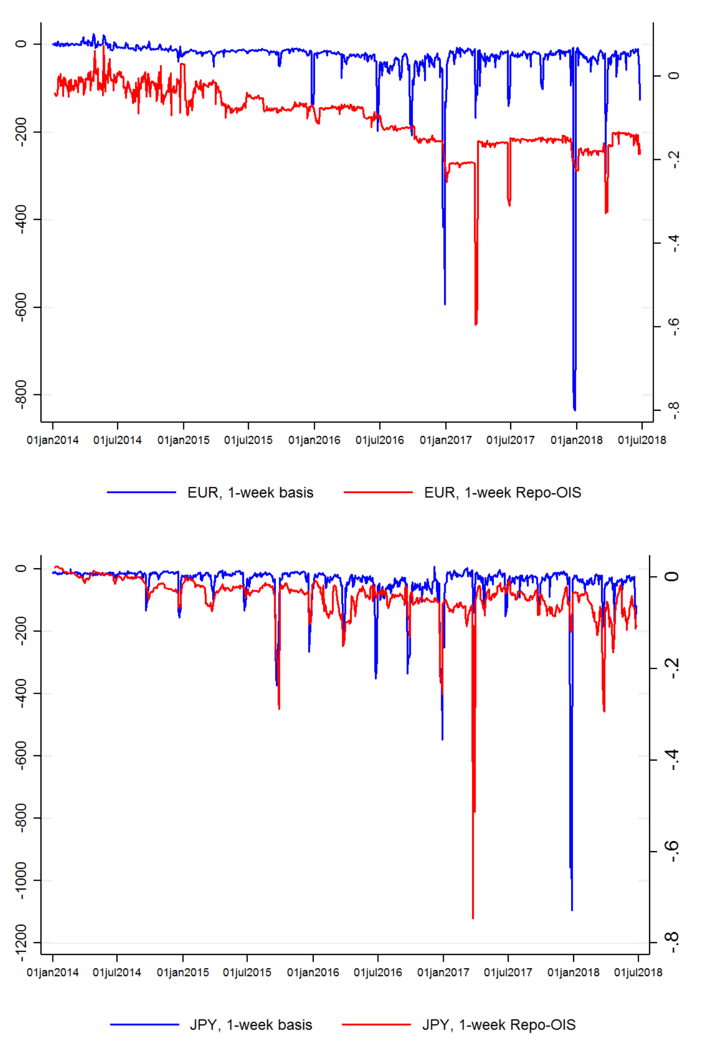



**Figure 10. 1-week CIP deviations, and repo market conditions in EUR and JPY.**

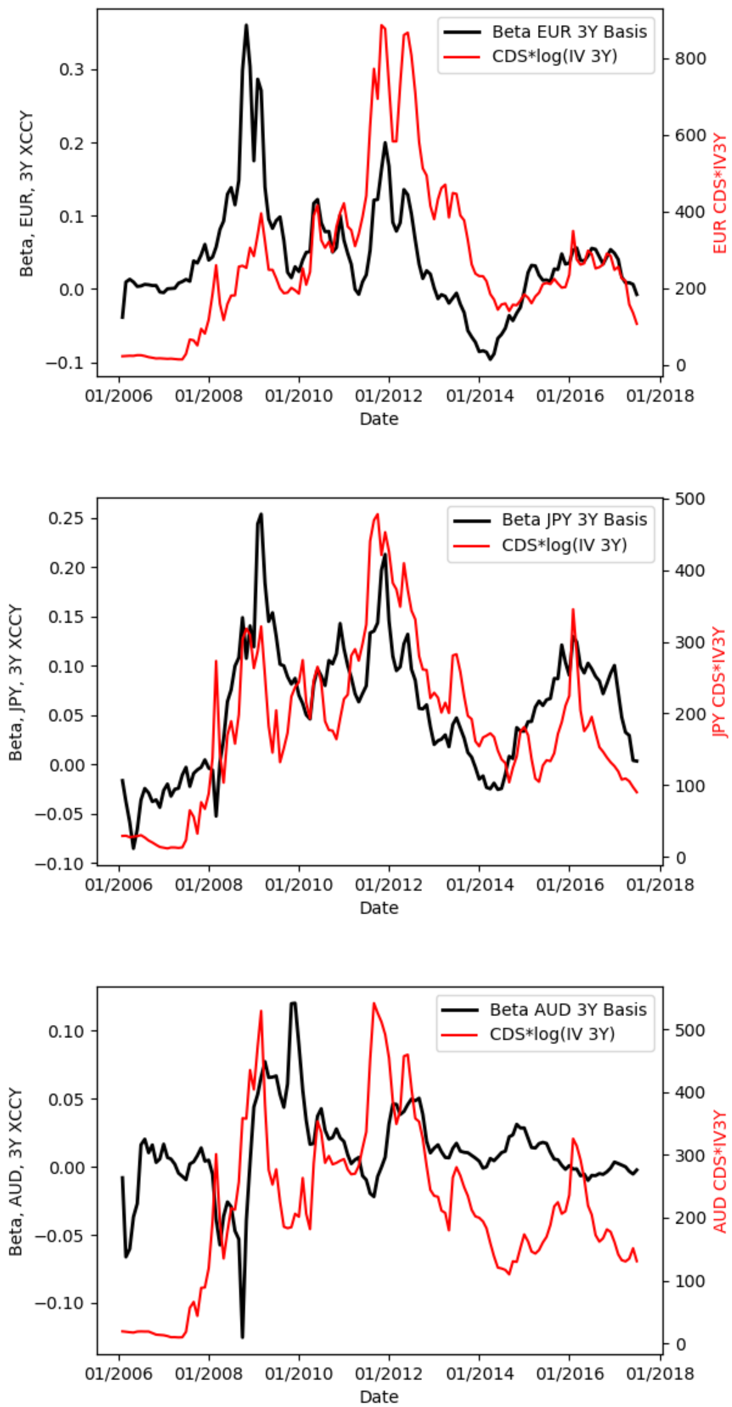



**Figure 11. Time-varying elasticity of 3-year currency basis response to FX hedging imbalances (coefficients estimated using Kalman filter) and interaction between banking sector CDS spreads ($\theta_t$) and FX option-implied volatility ($\rho\sigma_e^2$).**

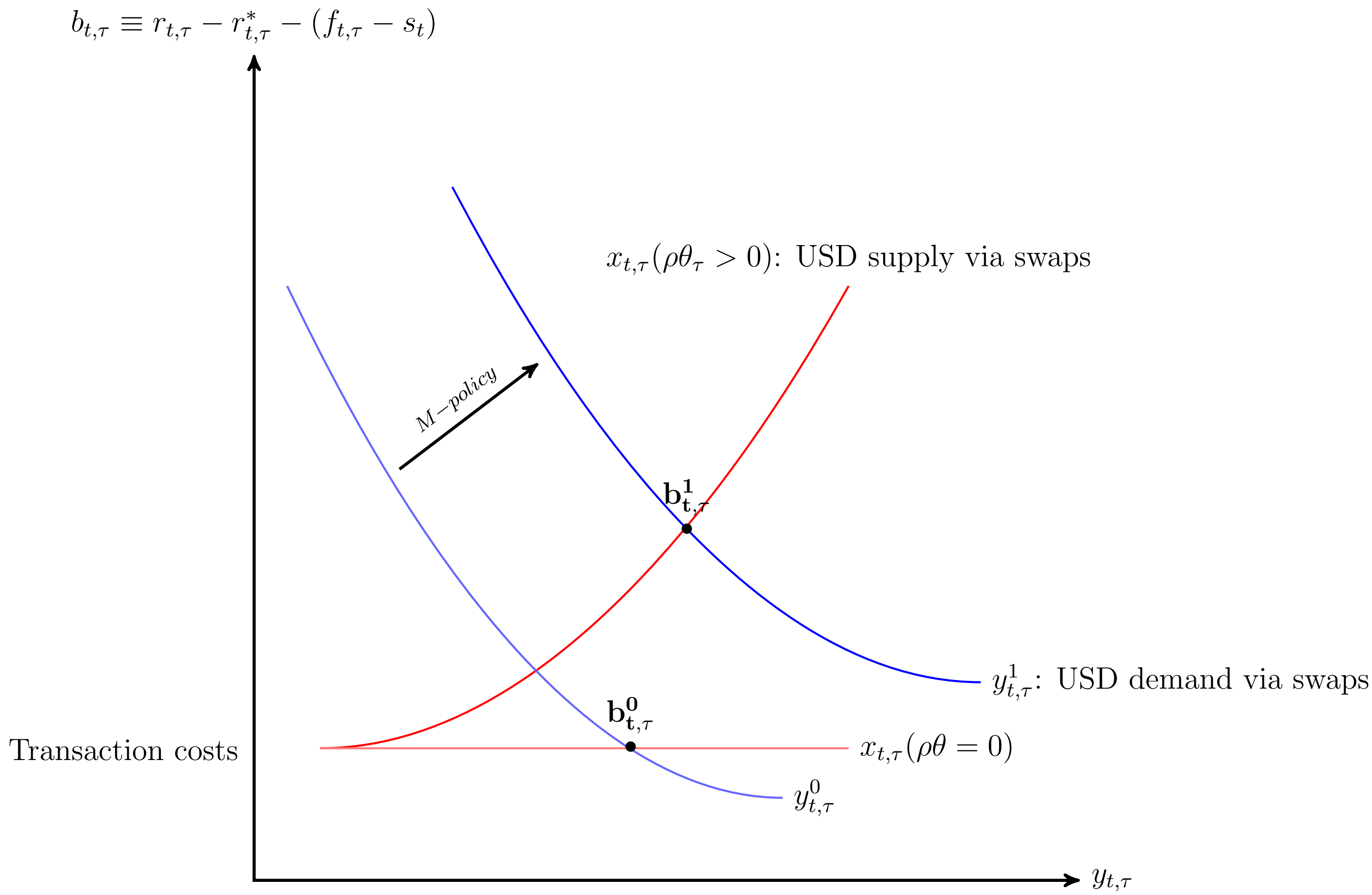



**Figure 12. Market-clearing currency basis**

# Tables

**Table I.** Exogenous variables

| Proxy: | Notation | Definition |
|---|---|---|
| FX hedging demand: | $y_t = y_t^B + y_t^I + y_t^C$ | Implied cross-currency position of banks institutional investors and corporates |
| | $y_t^B$ | BIS-reporting banks consolidated net off-balance sheet USD position |
| | $y_t^I$ | Institutional holdings of USD-denominated bonds $\times$ currency hedge ratio |
| | $y_t^C$ | Corporate cross-currency debt security liabilities |
| Risk: | $CDS_t$ | Banking sectors CDS spreads |
| | $VIX_t$ | CBOE S&P500 option-implied volatility index |
| Funding liquidity: | $OIS\ roll_t$ | Rollover risk - 1-month minus 1-week OIS spread differential in two currencies |
| | $Repo_t - OIS_t$ | 1-month GC Repo-OIS spread differential in two currencies |
| | $Deposit_t - OIS_t$ | 1-month bank deposit-OIS spread differential in two currencies |
| Market liquidity: | $FX$ bid-ask$_t$ | Spot FX bid-ask spreads |
| | $OISLiq_t$ | 1-month OIS bid-ask spreads |
| FX market risk: | $\rho\sigma_t^2$ | FX option-implied volatility |

**Table II.** Stationarity of CIP deviations across maturities: augmented Dickey-Fuller test (ADF) results for null hypothesis of unit root

| | EURUSD | | USDJPY | | AUDUSD | |
|---|---|---|---|---|---|---|
| Tenor: | Monthly | Daily | Monthly | Daily | Monthly | Daily |
| 1 week | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1 month | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 |
| 3 months | 0.007 | 0.006 | 0.000 | 0.000 | 0.000 | 0.000 |
| 6 months | 0.003 | 0.001 | 0.007 | 0.001 | 0.000 | 0.000 |
| 1 year | 0.079 | 0.037 | 0.414 | 0.333 | 0.007 | 0.002 |
| 2 years | 0.068 | 0.120 | 0.488 | 0.275 | 0.054 | 0.009 |
| 3 years | 0.087 | 0.127 | 0.382 | 0.408 | 0.109 | 0.061 |
| 5 years | 0.140 | 0.141 | 0.491 | 0.485 | 0.169 | 0.042 |
| 7 years | 0.171 | 0.185 | 0.508 | 0.502 | 0.159 | 0.316 |
| 10 years | 0.221 | 0.246 | 0.534 | 0.552 | 0.324 | 0.145 |
| 15 years | 0.282 | 0.282 | 0.591 | 0.490 | 0.171 | 0.364 |
| 20 years | 0.286 | 0.317 | 0.739 | 0.446 | 0.260 | 0.221 |
| 30 years | 0.277 | 0.273 | 0.813 | 0.371 | 0.037 | 0.217 |
| Number obs. in the time-series | 160 | 4,923 | 160 | 4,923 | 160 | 4,922 |

*Notes:* Augmented Dickey-Fuller test (ADF); automatic lag length selection based on SIC; probabilities for Fisher tests are computed using an asymptotic Chi-square distribution. All other tests assume asymptotic normality. Times-series of currency basis obtained from Bloomberg data on prices of cross-currency basis swaps, in basis points (bp). For EUR, 6-month tenors available only as of June 2008 and 3-month tenors available as of January 2008; for JPY, both 6-month and 3-month tenor become available as of August 2008; for AUD, both 6-month and 3-month tenors become available as of July 2011. For 1-week, 1-month, and 3-month and 6-month tenors, until basis swap data becomes available for the latter, cross currency basis constructed as follows: $\left\{\left(1+\frac{r_\tau}{100}\right)-\left[\left(1+\frac{r^*_\tau}{100}\right)\times\left(\frac{F_\tau}{S}\right)^{(360/\tau)}\right]\right\}\times 10000$; where $\tau$ is maturity in the number of days and $F_\tau$ denotes the forward exchange rate of maturity $\tau$ in the units of USD per foreign currency. For EUR and JPY, $r_\tau$ and $r^*_\tau$ are USD and foreign currency Libor rates of tenor $\tau$ in percentage points, while for AUD $r_\tau$ and $r^*_\tau$ are USD and AUD bank deposit rates of tenor $\tau$ because AUD Libor data not available, also expressed in percentage points.

**Table III.** Explained variance of first three principal components of CIP deviations at different maturities, as a fraction of extracted by principal component analysis (PCA)

| | EURUSD | USDJPY | AUDUSD |
|---|---|---|---|
| 1st factor ($F_1$) | 0.757 | 0.745 | 0.551 |
| 2nd factor ($F_2$) | 0.170 | 0.148 | 0.194 |
| 3rd factor ($F_3$) | 0.048 | 0.048 | 0.113 |
| Total | 0.975 | 0.940 | 0.859 |

*Notes:* For each currency cross, the sample consists of 1-month through 30-year currency basis, daily frequency, 01/01/2005 to 25/06/2018.

**Table IV.** Comparison of FX swap-implied Libor basis to FX swap-implied Repo basis; 1-week, 1-month, and 3-month tenors.

| | EURUSD | | | | | |
|---|---|---|---|---|---|---|
| | 1-week | | 1-month | | 3-month | |
| | Libor basis | Repo basis | Libor basis | Repo basis | Libor basis | Repo basis |
| Mean | -28.87 | -17.25 | -34.29 | -23.59 | -24.54 | -21.03 |
| Min | -835.81 | -260.82 | -282.41 | -182.30 | -99.09 | -70.50 |
| Std | 62.55 | 21.50 | 33.41 | 24.34 | 14.56 | 16.25 |
| | Difference: Libor basis minus Repo basis | | | | | |
| | % of repo basis | In bps | % of repo basis | In bps | % of repo basis | In bps |
| Mean | -67% | -11.62 | -45% | -10.70 | -17% | -3.51 |
| Min | -220% | -574.99 | -55% | -100.11 | -41% | -28.59 |
| Std | 191% | 41.05 | 37% | 9.07 | 10% | 1.70 |

| | USDJPY | | | | | |
|---|---|---|---|---|---|---|
| | 1-week | | 1-month | | 3-month | |
| | Libor basis | Repo basis | Libor basis | Repo basis | Libor basis | Repo basis |
| Mean | -42.77 | -37.27 | -47.56 | -44.56 | -35.58 | -43.78 |
| Min | -1095.12 | -1070.09 | -261.88 | -263.11 | -93.50 | -100.11 |
| Std | 76.54 | 69.30 | 37.35 | 33.80 | 18.35 | 19.35 |
| | Difference: Libor basis minus Repo basis | | | | | |
| | % of repo basis | In bps | % of repo basis | In bps | % of repo basis | In bps |
| Mean | -15% | -5.50 | -7% | -3.00 | 19% | 8.20 |
| Min | -2% | -25.03 | 0% | 1.23 | 7% | 6.61 |
| Std | 10% | 7.24 | 10% | 3.55 | 5% | 1.01 |

*Notes:* Daily frequency. 01/01/2014 to 25/06/2018 sample period. FX swap-implied basis constructed as follows: $\left\{\left(1+\frac{r_\tau}{100}\right)-\left[\left(1+\frac{r^*_\tau}{100}\right)\times\left(\frac{F_\tau}{S}\right)^{(360/\tau)}\right]\right\}\times 10000$; where $\tau$ is maturity in the number of days and $F_\tau$ denotes the forward exchange rate of maturity $\tau$ in the units of USD per foreign currency. For EUR and JPY, $r_\tau$ and $r^*_\tau$ are USD and foreign currency Libor rates and GC repo rates (for EUR, French GC repo rates used) of tenor $\tau$ in percentage points.

**Table V.** Cointegration test results for FX hedging demand in each currency pair with the first principal component of the currency basis term structure, *Empirical Level Factor* , or 3-year currency basis.

| | EURUSD | USDJPY | AUDUSD |
|---|---|---|---|
| | | 01/2006-07/2017 | |
| 1st factor ($F_1$) | 3.240* | 2.946 | 4.459** |
| *CIP Level* | 3.815** | 3.372* | 5.195*** |
| 3-year basis ($b_{3y}$) | 2.8192 | 6.192*** | 4.441** |
| | | 01/2008-07/2017 | |
| 1st factor ($F_1$) | 3.243* | 4.624** | 4.347** |
| *CIP Level* | 3.610* | 3.509* | 4.659** |
| 3-year basis ($b_{3y}$) | 3.135* | 7.279* | 3.785** |

*Notes:* Monthly frequency. Auto-regressive Distributive Lags (ARDL) bounds test for cointegration follows Pesaran, Shin, and Smith (2001); this test allows for breaks in the I(1) process for testing cointegration for processes characterised between I(0) and (1).

**Table VI.** Granger-causality between FX hedging demand and the first principal component, level factor, and 3-year currency basis.

| | EURUSD | | USDJPY | | AUDUSD | |
|---|---|---|---|---|---|---|
| | F-stat | p-val | F-stat | p-val | F-stat | p-val |
| $log(y_{t-1}) \nRightarrow F1_t$ | 4.180 ** | 0.043 | 8.800 *** | 0.004 | 2.871* | 0.093 |
| $F1_{t-1} \nRightarrow log(y_t)$ | 0.871 | 0.352 | 0.346 | 0.557 | 0.799 | 0.373 |
| $log(y_{t-1}) \nRightarrow CIP\ Level_t$ | 3.887 * | 0.051 | 14.949 *** | 0.000 | 6.732** | 0.011 |
| $CIP\ Level_{t-1} \nRightarrow log(y_t)$ | 0.640 | 0.425 | 0.027 | 0.869 | 0.268 | 0.606 |
| $log(y_{t-1}) \nRightarrow b_{3y,t}$ | 2.965 * | 0.086 | 13.576 *** | 0.000 | 1.500 | 0.223 |
| $b_{3y,t-1} \nRightarrow log(y_t)$ | 1.170 | 0.281 | 1.928 | 0.167 | 9.268 | 0.003 |

*Notes:* Monthly frequency, 01/2006 to 03/2018. 1-lag specifications: $y_t = \beta_y y_{t-1} + \beta_x x_{t-1} + \epsilon_t$. *** p<0.01, ** p<0.05, * p<0.1.

**Table VII.** ECM estimates of the drivers of the empirical *CIP Level* factor.

| | EURUSD | | USDJPY | | AUDUSD | |
|---|---|---|---|---|---|---|
| Error correction: | (1) | (2) | (1) | (2) | (1) | (2) |
| $\hat{z}_{t-1}$ | -0.110*** | -0.137*** | -0.195*** | -0.121** | -0.319*** | -0.372*** |
| | [-2.812] | [-3.312] | [-3.650] | [-2.039] | [-4.660] | [-5.302] |
| $\Delta log(y_{t-1})$ | -0.105 | 0.073 | -0.054 | -0.701 | 0.441 | 0.635 |
| | [-0.503] | [ 0.327] | [-0.042] | [-0.538] | [ 0.826] | [ 1.162] |
| Risk: | | | | | | |
| $\Delta CDS_t$ | -0.006*** | | -0.003** | | -0.004*** | |
| | [-5.013] | | [-2.193] | | [-2.398] | |
| $log(VIX_t)$ | | -0.227*** | | -0.260*** | | -0.173** |
| | | [-2.634] | | [-2.982] | | [-2.227] |
| Funding liquidity: | | | | | | |
| $OIS\ roll_t$ | -1.899*** | -1.813*** | -4.063*** | -4.050*** | -1.138*** | -1.070*** |
| | [-3.360] | [-3.010] | [-4.851] | [-4.926] | [-2.900] | [-2.716] |
| Market liquidity: | | | | | | |
| $FX$ bid-ask$_t$ | 0.008 | 0.008 | 0.010 | 0.028** | -0.003 | -0.005 |
| | [ 0.397] | [ 0.391] | [ 0.885] | [ 2.162] | [-0.301] | [-0.515] |
| $OISLiq_t$ | 0.023 | 0.154 | -0.022 | 0.143 | -0.049 | 0.066 |
| | [ 0.199] | [ 1.037] | [-0.200] | [ 1.196] | [-0.405] | [ 0.498] |
| Adj. R-squared | 0.265 | 0.165 | 0.413 | 0.433 | 0.186 | 0.181 |
| Cointegrating equation: | | | | | | |
| $log(y_t)$ | 0.770*** | | 3.203*** | | 0.879*** | |
| | [4.823] | | [15.586] | | [9.197] | |
| Adj. R-squared | 0.139 | | 0.634 | | 0.377 | |

*Notes:* Monthly frequency, 04/2006 to 07/2017 (05/2007 to 07/2017 for USDJPY); 136 (125 for USDJPY) observations (after adjustments). Coefficients on lagged dependent variable and constant omitted for brevity; number of lags of the endogenous variable chosen based on the Schwarz (Bayes) criterion (SC). Robust t-statistics in [ ]. *** p<0.01, ** p<0.05, * p<0.1.

**Table VIII.** ECM estimates of the drivers of 3-month cross-currency basis; cointegrating equation estimated using Kalman filter

| | EURUSD | USDJPY | AUDUSD |
|---|---|---|---|
| Error correction: | | | |
| $\hat{z}_{t-1}$ | -0.065** | -0.105** | -0.137*** |
| | [-1.763] | [-2.250] | [-3.046] |
| $\Delta y_{t-1}$ | -2.689 | 24.852 | 7.964* |
| | [-0.759] | [ 0.926] | [ 1.374] |
| $\Delta CDS_t$ | -0.132*** | -0.090*** | -0.026* |
| | [-6.732] | [-2.839] | [-1.458] |
| $OIS\ roll_t$ | -17.355** | -37.962** | 5.966* |
| | [-1.841] | [-2.040] | [ 1.401] |
| $FX$ bid-ask$_t$ | -0.061 | -0.238 | -0.099 |
| | [-0.176] | [-0.96500] | [-1.011] |
| $OISLiq_t$ | 0.162 | -2.713 | 1.951* |
| | [ 0.077] | [-1.031] | [ 1.611] |
| Adj. R-squared | 0.347 | 0.086 | 0.141 |
| Cointegrating equation: | | | |
| $log(y_t)$ | Time-varying $\hat{\alpha}_{y,t}$'s estimated using Kalman filter | | |

*Notes:* Monthly frequency, 04/2006 to 07/2017; 136 observations (after adjustments). Long-run cointegrating equation estimated using Kalman filter with time-varying coefficients on $log(y_t)$. In the error correction estimation results, coefficients on lagged dependent variable and constant omitted for brevity; number of lags of the endogenous variable chosen based on the Schwarz (Bayes) criterion (SC). Robust t-statistics in [ ]. *** p<0.01, ** p<0.05, * p<0.1.

# A. Technical Appendix

## A. *Principal component analysis*

Drawing on the description in Wellmann and Truck (2018), assume $B$ to be a $T \times N$ matrix of standardized currency basis for each maturity $\tau$, $\Delta b_t^\tau$ , where $T$ is the number of maturities and $N$ is the number of observation dates. To derive the orthogonal factors $F_{1,...K}$ that can account for the variability of the term structure, the PCA computes an orthogonal $K \times T$ matrix $\Gamma$ in order to extract factors $F_K$ and factor loadings $\gamma_K$:

$$\Gamma B = \Phi$$

where $\Phi$ is a $K \times N$-dimentional matrix of latent factors $F$. The $T \times T$ covariance matrix of $S$ can be decomposed as:

$$\Sigma = \Gamma \Lambda \Gamma'$$

where the diagonal elements of $\Lambda$ are the eigenvalues and the columns of $\Gamma$ are the eigenvectors. Arranged in decreasing order of the eigenvalues, the first $K$ eigenvectors of $\Gamma$ denote the factor loadings $[\gamma_1, ..., \gamma_K]$ and the $K$ latent factors are defined by $F_{k,t} = \gamma_k^{'} B_t$.

### B. *Objection functions under CARA-normal assumption*

Substituting equation (3) into the utility function and assuming exchange rate returns are log-normally distributed, such that equation (4) holds, we have that,

$$
\begin{aligned}
\mathbb{E}_t[U(\mathrm{d}W_t)] &= \int_{-\infty}^{\infty} -\exp\left(-\rho\left\{\left(W_t - \int_0^T x_{t,\tau}\mathrm{d}\tau\right) r_{t,\tau} + \int_0^T (1-\theta_{t,\tau})x_{t,\tau}(f_{t,\tau} - s_t + r^*_{t,\tau}\mathrm{d}\tau\right.\right. \\
&+ \left.\left.\int_0^T \theta_{t,\tau}x_{t,\tau}(f_{t,\tau} - s_t + r^*_t)\mathrm{d}\tau\right\}\mathrm{d}s \times \frac{1}{\sqrt{2\pi\sigma^2_{t,\tau}}}\exp\left\{\frac{-\theta_{t,\tau}(s_t - \mathbb{E}_t(\mathrm{d}s_t))^2)}{2\sigma^2_s}\right\}\right) \\
&= -\exp\left\{\frac{-\rho}{\sqrt{2\pi\sigma^2_{t,\tau}}}\left[\left(W_t - \int_0^T x_{t,\tau}\mathrm{d}\tau\right) r_{t,\tau} + \int_0^T x_{t,\tau}(f_{t,\tau} - s_t + r^*_{t,\tau})\mathrm{d}\tau\right.\right. \\
&- \left.\left.\frac{\rho\sigma^2_{t,\tau}}{2}\left(\int_0^T \theta_{t,\tau}x_{t,\tau}\mathrm{d}\tau\right)^2\right]\right\} \qquad \text{(B1)}
\end{aligned}
$$

where the last line follows from using standard properties of CARA-normal optimization. Then, the objective function reduces to the following certainty-equivalent:

$$
\left(W_t - \int_0^T x_{t,\tau}\mathrm{d}\tau\right) r_t + \int_0^T x_{t,\tau}(f_{t,\tau} - s_t + r^*_t)\mathrm{d}\tau - \int_0^T \frac{\rho\sigma^2_{t,\tau}}{2}d\tau\left(\int_0^T \theta_{t,\tau}x_{t,\tau}d\tau\right)^2. \qquad \text{(B2)}
$$

### C. *Kalman filter*

State models in general consist of a measurement equation (equation (7)) linking observations of our dependent variables (the first principal component, empirical level factor, or 3-year currency basis for each currency) to our latent state variable (FX hedging demand) and a transition equation (equation (8)) which describes the evolution of the state variable according to a Markov process. The Kalman filter, in its simplest form, is a recursive procedure based on prediction, updating, and likelihood estimation that allows us to solve state space models. We use a simple textbook example of Kalman filtering to estimate the state space model in equations (7) and (8)[21,22]. At each time $t$, we require an optimal predictor of $y_t$ conditional on all available information up until

[21]See Hamilton (1994) for a much more detailed overview of Kalman filters and state space models.

[22]To clarify notation, the conditional expectation and covariance of $\beta$ given time $t-1$ ($t$) information is $\beta_{t|t-1} = \mathbb{E}[\beta_t|I_{t-1}]$ ($\beta_{t|t} = \mathbb{E}[\beta_t|I_t]$) and $P_{t|t-1} = \mathbb{E}[(\beta_t - \beta_{t|t-1})(\beta_t - \beta_{t|t-1})']$ ($P_{t|t} = \mathbb{E}[(\beta_t - \beta_{t|t})(\beta_t - \beta_{t|t})']$) respectively. The prediction error given time $t-1$ information is given by $\eta_{t|t-1} = y_t - y_{t|t-1} = y_t - x'_t\beta_{t|t-1}$ and the conditional variance of the prediction error is given by $f_{t|t-1} = \mathbb{E}[\eta^2_{t|t-1}]$

time $t-1$. Therefore, we predict $\beta_{t|t-1}, P_{t|t-1}$ and $y_{t|t-1}$ by

$$\beta_{t|t-1} = c + F\beta_{t-1|t-1} \tag{C1}$$

$$P_{t|t-1} = FP_{t-1|t-1}F^{'} + Q \tag{C2}$$

$$y_{t|t-1} = x_t^{'}\beta_{t|t-1}. \tag{C3}$$

Upon realization of $y_t$ at each $t$, the prediction error $\eta_{t|t-1}$ is calculated and contains new information about $\beta_t$. We then have that

$$f_{t|t-1} = x_t P_{t|t-1} x_t^{'} + R \tag{C4}$$

$$\beta_{t|t} = \beta_{t|t-1} + K_t \eta_{t|t-1} \tag{C5}$$

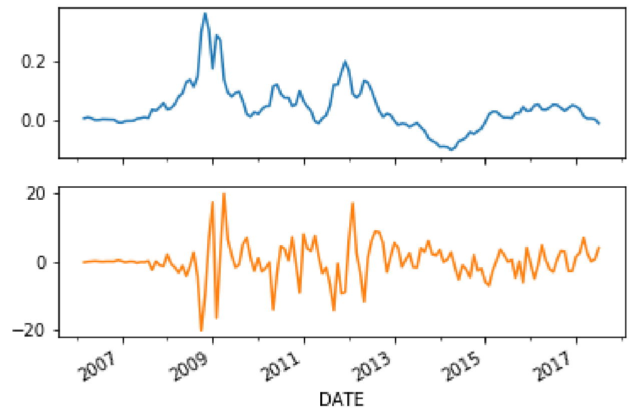
$$P_{t|t} = P_{t|t-1} - K_t x_t P_{t|t-1} \tag{C6}$$

where $K_t$ is the Kalman gain matrix at time $t$ and given by

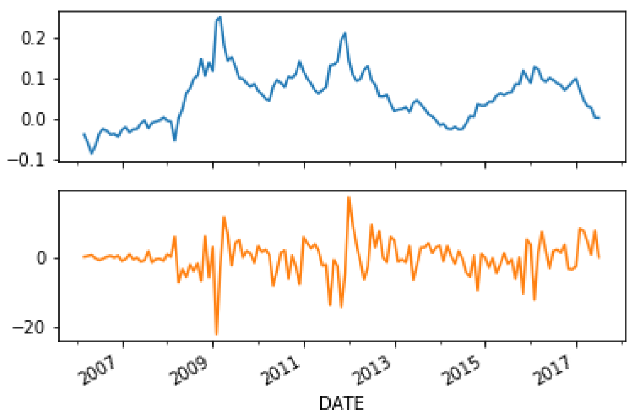
$$K_t = P_{t|t-1} x_t^{'} f_{t|t-1}^{-1}. \tag{C7}$$

The algorithm we estimate runs as follows: (i) choose initial values for $\beta_{0|0} = \mathbf{0}$ and $P_{0|0} = \mathbf{1}$; (ii) iterate equations (C1) - (C3) forward for prediction and similarly iterate equations (C4) - (C6) forward for the updates for $t = 1, 2, ...T$ where our observations' frequency is monthly starting in January 2006 and ending in July 2017; (iii) construct and maximize the likelihood function[23]; (iv) re-run the filter to extract the time series of time-varying parameters $\{\beta_t, e_t\}$ for the model in (7) and (8) for each currency.

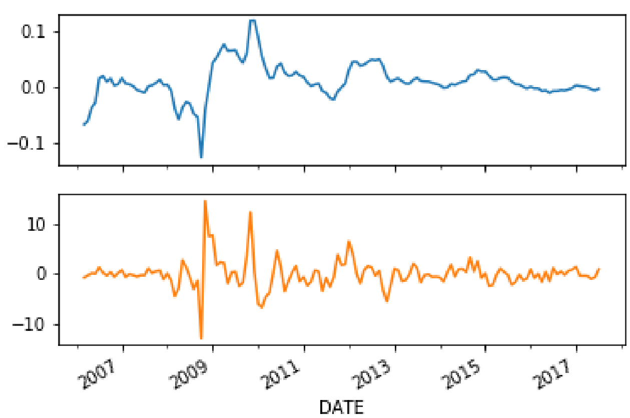
[23] Assuming that $\beta_0$ and $\{e_t, \nu_t\}$ are Gaussian then $y_t|I_{t-1} \sim N(y_{t|t-1}, f_{t|t-1})$ and, hence, the log-likelihood of each observation at time $t$ is given by $l_t = -\frac{1}{2}\ln(2\pi) - \ln f_{t|t-1} - \eta_{t|t-1}^{'} f_{t|t-1}^{-1} \eta_{t|t-1}$ which is maximized with respect to the unknown parameters.




(a) EUR, 3-year currency basis




(b) JPY, 3-year currency basis




(c) AUD, 3-year currency basis

**Figure A1. Time-varying estimates of $\beta_t - \beta_{t-1}$ and $e_t - e_{t-1}$ for 3-year currency basis.**

# B. Additional Figures & Tables

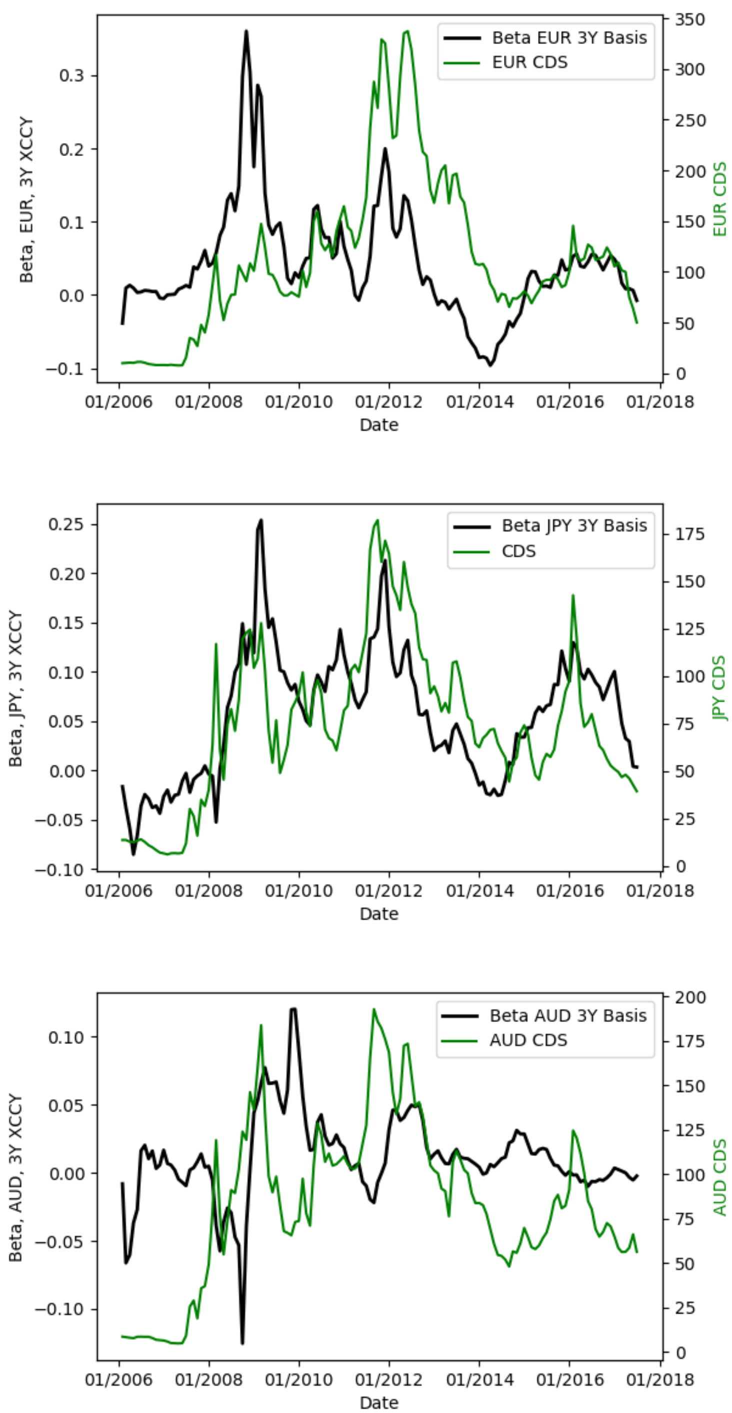



**Figure B1. Time-varying elasticity of 3-year currency basis response to FX hedging imbalances (coefficients estimated using Kalman filter) and banking sector CDS spreads ($\theta_t$).**

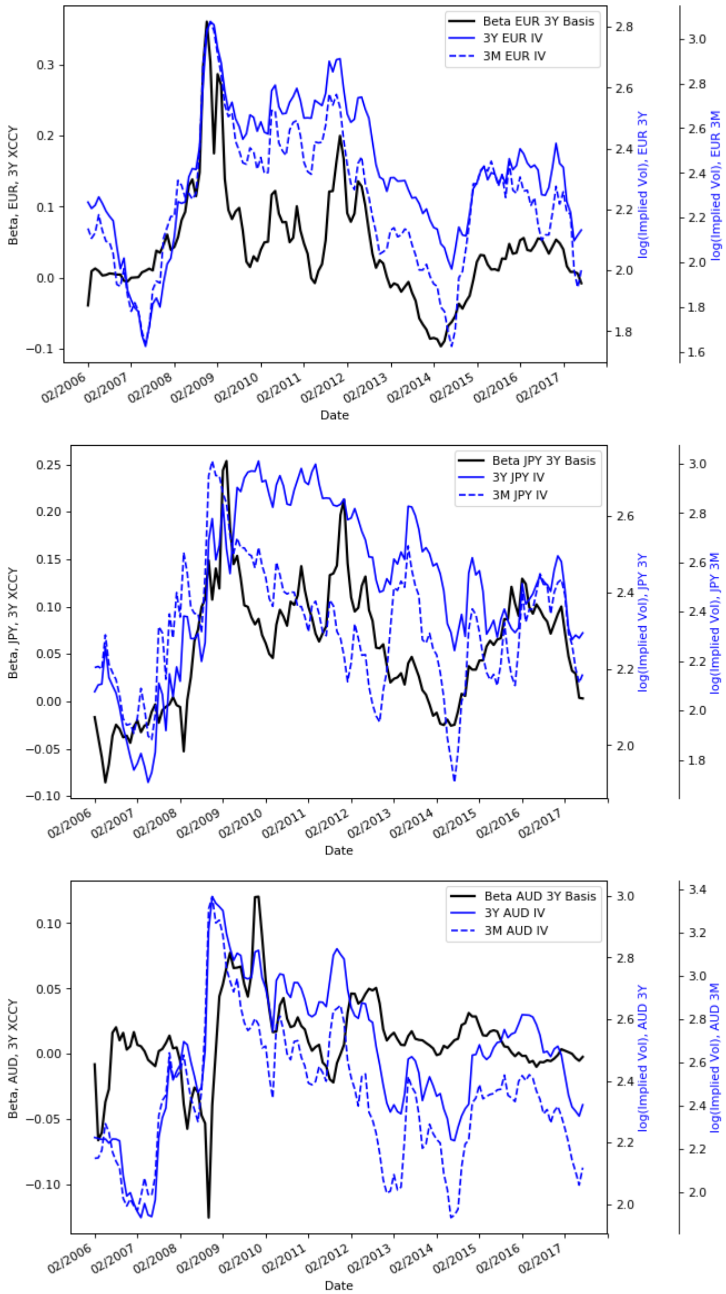



**Figure B2. Time-varying elasticity of 3-year currency basis response to FX hedging imbalances (coefficients estimated using Kalman filter) and FX option-implied volatility ($\rho\sigma_e^2$).**

**Table B1.** ECM estimates of the drivers of 3-year cross-currency basis

| | EURUSD | | USDJPY | | AUDUSD | |
|---|---|---|---|---|---|---|
| Error correction: | (1) | (2) | (1) | (2) | (1) | (2) |
| $\hat{z}_{t-1}$ | -0.079*** | -0.106*** | -0.176*** | -0.142*** | -0.145*** | -0.144*** |
| | [-2.742] | [-3.442] | [-4.180] | [-3.189] | [-3.032] | [-2.899] |
| $\Delta log(y_{t-1})$ | -2.323 | 1.708 | 4.500 | -0.511 | 8.735* | 9.073* |
| | [-0.670] | [ 0.451] | [ 0.169] | [-0.019] | [ 1.498] | [ 1.487] |
| Risk: | | | | | | |
| $\Delta CDS_t$ | -0.125*** | | -0.082*** | | -0.024* | |
| | [-6.391] | | [-2.628] | | [-1.372] | |
| $log(VIX_t)$ | | -5.726*** | | -5.055**** | | -0.357 |
| | | [-4.006] | | [-2.828] | | [-0.428] |
| Funding liquidity: | | | | | | |
| $OIS\ roll_t$ | -22.904*** | -20.421** | -44.899*** | -45.885*** | 5.863* | 6.173* |
| | [-2.419] | [-1.994] | [-2.542] | [-2.605] | [ 1.373] | [ 1.431] |
| Market liquidity: | | | | | | |
| $FX$ bid-ask$_t$ | 0.061 | 0.097 | -0.007 | 0.284 | -0.030 | -0.034 |
| | [ 0.192] | [ 0.283] | [-0.029] | [ 1.099] | [-0.314] | [-0.349] |
| $OISLiq_t$ | -0.733 | 2.546 | -0.842 | 2.723 | 0.980 | 1.312 |
| | [-0.353] | [ 0.989] | [-0.371] | [ 1.067] | [ 0.826] | [ 0.954] |
| Adj. R-squared | 0.265 | 0.165 | 0.413 | 0.433 | 0.186 | 0.181 |
| Cointegrating equation: | | | | | | |
| $log(y_t)$ | 13.326*** | | 128.147*** | | 14.293*** | |
| | [3.622] | | [24.454] | | [11.320] | |
| Adj. R-squared | 0.081 | | 0.810 | | 0.480 | |

*Notes:* Monthly frequency, 04/2006 to 07/2017 (05/2007 to 07/2017 for USDJPY); 136 (125 for USDJPY) observations (after adjustments). Coefficients on lagged dependent variable and constant omitted for brevity; number of lags of the endogenous variable chosen based on the Schwarz (Bayes) criterion (SC). Robust t-statistics in [ ]. *** p<0.01, ** p<0.05, * p<0.1.

**Table B2.** ECM estimates of the drivers of the empirical *CIP Level* factor; alternative funding liquidity proxies.

| | EURUSD | | USDJPY | | AUDUSD | |
|---|---|---|---|---|---|---|
| Error correction: | (1) | (2) | (1) | (2) | (1) | (2) |
| $\hat{z}_{t-1}$ | -0.073 ** | -0.095 ** | -0.166 *** | -0.477 *** | -0.302 *** | -0.348 *** |
| | [-1.857] | [-2.095] | [-3.275] | [-6.485] | [-4.355] | [-4.844] |
| $\Delta y_{t-1}$ | -0.144 | -0.191 | -2.346 ** | -0.784 | 0.413 | 0.439 |
| | [-0.679] | [-0.925] | [-1.851] | [-0.626] | [ 0.754] | [ 0.807] |
| $\Delta CDS_t$ | -0.006 *** | -0.005 *** | -0.002 * | -0.002 | -0.004 ** | -0.001 |
| | [-5.080] | [-4.569] | [-1.317] | [-1.163] | [-2.138] | [-0.752] |
| $Dep_t - OIS_t$ | -0.289 *** | | -0.325 *** | | -0.165 ** | |
| | [-2.604] | | [-4.279] | | [-1.952] | |
| $Repo_t - OIS_t$ | | 0.377 *** | | -0.420 * | | 0.681 *** |
| | | [ 2.611] | | [-1.637] | | [ 3.224] |
| Post2014 | | -0.047 | | -0.016 | | -0.181 * |
| | | [-0.817] | | [-0.249] | | [-1.547] |
| Post2014$\times Repo_t - OIS_t$ | | -2.017 *** | | -2.386 *** | | -1.134 ** |
| | | [-3.178] | | [-4.802] | | [-2.034] |
| $FX$ bid-ask$_t$ | 0.003 | 0.023 | 0.008 | -0.015 | -0.008 | -0.009 |
| | [ 0.138] | [ 1.104] | [ 0.758] | [-1.327] | [-0.905] | [-0.869] |
| $OISLiq_t$ | -0.047 | -0.020 | 0.075 | -0.065 | -0.132 | -0.045 |
| | [-0.399] | [-0.160] | [ 0.741] | [-0.605] | [-1.107] | [-0.376] |
| Adj. R-squared | 0.240 | 0.274 | 0.387 | 0.519 | 0.157 | 0.189 |
| Cointegrating equation: | | | | | | |
| $log(y_t)$ | 0.770*** | | 3.203*** | | 0.879*** | |
| | [4.823] | | [15.586] | | [9.197] | |
| Adj. R-squared | 0.139 | | 0.634 | | 0.377 | |

*Notes:* Monthly frequency, 04/2006 to 07/2017 (05/2007 to 07/2017 for USDJPY); 136 (125 for USDJPY) observations (after adjustments). Coefficients on lagged dependent variable and constant omitted for brevity; number of lags of the endogenous variable chosen based on the Schwarz (Bayes) criterion (SC). Robust t-statistics in [ ]. *** p<0.01, ** p<0.05, * p<0.1.