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Abstract

We show that it is crucial to account for the heterogeneity in funding costs, both across banks and across currency areas, in order to understand recently documented deviations from Covered Interest Parity (CIP). When CIP arbitrage is implemented accounting for marginal funding costs and realistic risk-free investment instruments, the no-arbitrage relation holds fairly well for the majority of market participants. A narrow set of global high-rated banks, however, does enjoy riskless arbitrage opportunities. Such arbitrage opportunities emerge as an equilibrium outcome as FX swap dealers set prices to avoid inventory imbalances. Low-rated banks find it attractive to turn to the FX swap market to cover their U.S. dollar funding, while swap dealers elicit opposite (arbitrage) flows by high-rated banks. Such arbitrage opportunities are difficult to scale, with funding rates adjusting as soon as arbitrageurs increase their positions.

JEL Classification: E43, F31, G15

Keywords: Covered Interest Parity, U.S. Dollar Funding, Funding Liquidity Premia, FX Swap Market

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Covered Interest Parity Arbitrage*

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1. Introduction

The persistent deviation from Covered Interest Parity (CIP) in major currencies, as some common measures indicate, has been one of the most puzzling phenomena in international financial markets in recent years.[1] The concept of CIP builds on the principle of 'no-arbitrage' – the most fundamental mechanism in financial markets. It postulates that it is impossible to earn a profit by borrowing in one currency and lending in another, while fully covering the foreign exchange (FX) risk. The pricing in money markets and in FX swaps should adjust so that it is not possible to reap risk-free profits (net of costs) on a self-financed strategy. Studying why a fundamental no-arbitrage relation such as CIP breaks down offers unique insights into the functioning of some of the world's largest and systemically important financial markets and the constraints faced by the key players operating in them.[2]

But, when it comes to arbitrage, the devil is in the details. Testing the validity of a no-arbitrage condition such as CIP requires carefully accounting for the key costs and inherent risks in the arbitrage trade. Obviously, accounting for transaction costs is important. However, as we stress in this paper, it is even more important to account for the *marginal funding cost* the arbitrageur faces and to make sure the trade is indeed *risk-free* from the arbitrageur's perspective.

Taking these considerations seriously in our empirical tests, we find that CIP does in fact hold quite well for the majority of market participants – even though commonly used aggregate measures may indicate seemingly large arbitrage profits in recent years. As we show in this paper, the set of potential CIP arbitrageurs is fairly narrow, with only a few high-rated banks in a position to reap economically attractive arbitrage profits. We show how a situation with persistent arbitrage opportunities emerges as an equilibrium outcome in international money markets, when banks are heterogeneous in their U.S. dollar (USD) funding costs and funding liquidity premia diverge across major currency areas. We provide evidence based on FX swap order flow data consistent with our

[1] See, inter alia, BIS (2015), Barclays (2015), Pinnington and Shamloo (2016), Du, Tepper, and Verdelhan (2018), Shin (2016), BIS (2016), Borio, McCauley, McGuire, and Sushko (2016), Avdjiev, Du, Koch, and Shin (2018), and Arai, Makabe, Okawara, and Nagano (2016).

[2] The key subject of study of this paper is the market for FX swaps – a derivative contract consisting of a simultaneous combination of a spot transaction and an opposite forward. FX swaps are traded OTC and are widely used by market participants to facilitate cross-border borrowing and investment and to manage exposure to FX risk. Banks use FX swaps for liquidity management in different currencies and the management of currency risk. By any standards, the FX swap market is huge with a daily trading volume exceeding USD 2 trillion (BIS, 2016).

framework, and rely on issuance data on short-term USD funding instruments to show that any CIP arbitrage opportunities are difficult to scale.

Before the Global Financial Crisis (GFC), Akram, Rime, and Sarno (2008) found, based on carefully constructed high-frequency data and taking account of transaction costs, that any CIP deviations were too small and short-lived to give rise to economically significant arbitrage profits. Since the onset of the GFC, however, seemingly large CIP deviations have emerged, even involving some of the world's most liquid currencies (such as the euro (EUR), the Japanese yen (JPY) and the Swiss franc (CHF)). The breakdown of no-arbitrage during the height of the GFC and of the European sovereign debt crisis — periods which saw price dislocations across many asset classes — may not be surprising. However, e.g. Du, Tepper, and Verdelhan (2018) suggest that the anomaly has been particularly severe during the much calmer period since 2013. This stands in contrast to the above-mentioned pre-crisis evidence and, more generally, the basic principles of financial economics, and has puzzled academics, central bankers and market participants alike.

To make progress in the understanding of the CIP puzzle, we address how the main CIP arbitrageurs would approach the question of whether it is economically attractive to enter into the trade. We focus on short-term (1-week to 3-month) arbitrage opportunities for global banks. Banks operate in funding markets in multiple currencies, have broad access to short-term risk-free assets, face constant funding/liquidity needs and can flexibly choose the cost-optimal funding option.

In focussing on implementable arbitrage from the perspective of global banks, our approach deviates from the extant CIP literature in several important ways. *First*, we argue that it is critical to rely on money market rates that adequately capture fluctuations in banks' marginal funding costs when testing the CIP no-arbitrage condition. Against the backdrop of significant structural changes in money markets over the past decade, the task of selecting the appropriate interest rates is not straightforward. There is wide dispersion in short-term borrowing rates faced by participants in various segments in USD money markets (as shown, e.g., by Duffie and Krishnamurthy, 2016). Heterogeneity in funding costs (both across banks in USD markets and across major currency areas) makes it impossible for a single FX swap rate to ensure that the 'law of one price' (LOOP) holds for the full spectrum of short-term interest rates. Such heterogeneity in funding rates was not present pre-GFC as different rates lay virtually on top of each other, but has become a salient feature of today's money markets. Arbitrage incentives will hence differ substantially across banks and vary by their marginal funding costs. The law of one price may hold for one set of market participants, but not for others.

Second, we argue that it is important to treat the funding and investment leg of CIP arbitrage trades differently. For the funding leg, it is no longer appropriate to look at interbank rates (such as LIBOR) – a market where activity has dwindled due to regulatory changes and excess liquidity created by central banks' asset purchase programs (e.g., Schrimpf and Sushko, 2019). Instead, it is necessary to turn to those interest rates at which banks can raise wholesale money market funding from non-bank investors. We focus on Commercial Paper (CP) and Certificates of Deposit (CD), i.e. short-term unsecured funding instruments issued by banks that are typically held by money market funds (MMFs) or other institutional investors. We show that for CP rates (unlike for other interest rates), deviations from LOOP are in fact fairly small — in stark contrast to, e.g., interbank offered (IBOR) or Overnight-Index-Swap (OIS) rates.

Moreover, when testing the CIP no-arbitrage condition, it is important to allow for the rate in the investment leg of the strategy to differ from that in the funding leg so as to ensure that the trade is truly risk-free. As riskless investment vehicles we therefore consider both deposit facilities of foreign central banks and short-term government securities (T-bills). While all market participants have access to government securities, only a subset of globally active banks (i.e. central bank eligible counterparties) can deposit funds at the central bank deposit facility rate. T-bill rates will respond to demand pressure generated by arbitrage, whereas the interest on reserves deposited in central banks' deposit facilities is insensitive to volume.

Based on this empirical setup, we find that *risk-free* CIP arbitrage opportunities do indeed exist over our post-crisis sample period – but only for a limited set of market participants. The vast majority of banks around the globe face prohibitively high marginal funding costs in USD. Economically viable arbitrage opportunities are available only to a narrow set of high-rated banks that have access to favorable USD CP or CD funding and can invest at the deposit facilities of foreign central banks (i.e. a risk-free investment vehicle). Such arbitrage opportunities are less attractive if short-term government securities are the only risk-free investment asset available.

Third, we study the challenges for intermediaries of quoting FX swap rates against the backdrop of imbalances in the demand and supply of USD in the FX swap market.[3] We start by conceptually characterising the constellation in FX swaps and international money markets in a situation when funding liquidity premia in different currency areas diverge. A situation like this has been an important feature of money markets in recent years due to the excess liquidity created by the balance sheet policies of major central banks outside of the US. While unsecured non-bank USD funding markets have remained highly fragmented, with a large dispersion in funding costs across banks, we show that funding liquidity premia have significantly compressed in other key currency areas (in particular, JPY, EUR and CHF) due to the abundance of central bank reserve balances.

We present evidence based on quantities (FX swap order flow) consistent with this framework. To control his inventory in the market environment outlined above, a swap dealer aiming to balance order flow from customers needs to quote FX swap prices so as to incentivize flows in both directions. Consistent with our interpretation that relative funding conditions across currencies matter significantly for the pricing distortions, we find that the price impact of swap order flow is particularly elevated in situations when it is attractive for banks at the bottom of the credit rating distribution to turn to the FX swap market to obtain USD funding. Faced with such imbalances (which tend to coincide with broader funding constraints in the USD), swap dealers revise their quotes to attract matching opposite flow. As a consequence, a set of market players may enjoy arbitrage opportunities. For this to constitute an equilibrium, market forces must exist that limit the size of the arbitrage flows to match the opposing flows. To our knowledge, this is the first paper investigating the role of order flow as a determinant of pricing in the FX swap market.

Finally, we therefore study whether there are limits to the scalability of the arbitrage trades enjoyed by high-rated banks. To this end, we rely on panel regressions using transaction-level data for short-term CD issuances in USD markets. Our results indicate that with reasonably large increases in issuance volumes, much of the CIP arbitrage profit is wiped out by the increase in USD funding costs.

[3] FX swap market makers, the ones that actually set FX swap quotes, extract intermediation markups from the bid-ask spread, but have strong incentives to balance customer order flow. See e.g. Evans and Lyons (2002) on how market makers control inventory in the FX spot market. The basic principles also apply for simple derivatives such as FX swaps or forwards.

Related literature. The GFC has, unsurprisingly, revitalized research interest in the validity of the CIP condition. A first wave of papers, e.g. Baba, Packer, and Nagano (2008) and Baba and Packer (2009), focused on the USD funding shortages of global banks as a key driver of the relationship's breakdown.[4] Based on this research, and more recently Bahaj and Reis (2018), a consensus emerged that the provision of USD liquidity via major central banks' swap lines with the Federal Reserve was instrumental in alleviating the dollar shortage and helped to significantly ease the CIP dislocation.

Our paper is mostly related to a second wave of research that seeks to explain why deviations have been so persistent in the post-GFC environment — even in the absence of any obvious market stress. Du, Tepper, and Verdelhan (2018) carefully document the price dislocations, stressing in particular the importance of bank regulations, and suggest a causal link from regulation to CIP deviations. Sushko, Borio, McCauley, and McGuire (2016) highlight the role of FX hedging demand as an important driver.[5] Iida, Kimura, and Sudo (2016), Wong and Zhang (2018) and Wong, Leung, and Ng (2016) stress the importance of counterparty risk.[6]

Last, but not least, our work relates more broadly to work emphasizing the role of intermediation frictions and the role of limits to arbitrage.[7] Gabaix and Maggiori (2015) provide an equilibrium model where intermediation frictions and segmentation effects can lead to the failure of both uncovered and covered interest parity. The results in our paper are also linked to theoretical work emphasizing the constraints faced by arbitrageurs in segmented markets (e.g. Gromb and Vayanos, 2002), frictions in funding markets (e.g. Brunnermeier and Pedersen, 2009; Gârleanu and Pedersen, 2011) and slow-moving capital (e.g. Mitchell, Pedersen, and Pulvino, 2007; Duffie, 2010).

Roadmap. The rest of the paper is structured as follows. Section 2 lays out the main concepts and the data requirements. Section 3 investigates LOOP violations and CIP arbitrage in international

[4]Other important contributions include Coffey, Hrung, Nguyen, and Sarkar (2009), Gârleanu and Pedersen (2011), Goldberg, Kennedy, and Miu (2011), Griffoli and Ranaldo (2010), McGuire and von Peter (2012), Bottazzi, Luque, Pascoa, and Sundaresan (2012), and Syrstad (2014).

[5]Cenedese, Della Corte, and Wang (2018) use trade repository volume data to study limits to arbitrage and to study imbalances in the dealer-to-customer segment of the FX swap market.

[6]A common explanation for observed deviations from the law of one price based on IBOR rates is differences in the default risk premium across currencies (Tuckman and Porfirio, 2003). If the interest rates in the two currencies are subject to different credit risk premia, any deviations cannot be seen as an arbitrage opportunity.

[7]See Shleifer and Vishny (1997) for the seminal contribution on limits to arbitrage, and e.g. Gromb and Vayanos (2010) for a survey of theoretical literature.

money markets based on a realistic assessment of marginal funding costs. It focuses on the heterogeneity of banks' borrowing costs in the commercial paper market and quantifies the magnitude of riskless arbitrage profits involving the remuneration of reserves on behalf of central banks. Section 4 explores equilibrium dynamics in the FX swap market from a market maker perspective in a world with segmented money markets and abundance of central bank reserve balances. It presents results on the price impact of order flow and explores the forces that impede arbitrage. In Section 5, we address the striking patterns occuring around End-of-Quarter and End-of-Year and show how these are consistent with other results in the paper relating to differences in liquidity. Section 6 concludes. A separate Online Appendix contains supplementary material.

2. CIP arbitrage: concepts and data

This section provides definitions of some key terms and provides an overview of our dataset. A main goal of this section is further to show that the choice of money market rates is a non-trivial, yet crucial, input for the study of covered interest parity violations in the post-GFC world.

2.1. LOOP vs CIP

In this paper, we distinguish between two main concepts in international money markets — the Law of One Price (LOOP) and Covered Interest Parity (CIP). Our focus is on the no-arbitrage condition known as CIP, but to understand market dynamics in the FX swap market, it will be necessary to refer to LOOP as well.

Law of one price violations. The law of one price condition implies that borrowing costs in similar funding vehicles should be equal across currencies. To assess deviations from LOOP, we compare the *direct* borrowing costs in currency B money markets with the *implied* borrowing costs (based on the FX swap market). The latter are given by the costs of raising funds in e.g. USD money markets, converting the funds into e.g. euros while at the same time hedging the currency risk.

Testing LOOP is not the same as testing for the existence of no-arbitrage. Instead, LOOP deviations represent an opportunity for borrowers to fund a *given* position in an asset more cheaply by raising funds in another currency and hedging the FX risk via the FX swap market.[8]

Covered interest parity. CIP is based on the basic proposition that a *self-financed, risk-free* arbitrage trade — borrowing in e.g. USD, investing in a risk-free asset in e.g. euros, and using an FX swap in order to ensure riskless conversion of the proceeds — should not yield any profits.

To exploit CIP deviations, the arbitrageur has to perform a full *round-trip* of trades, which we illustrate with the sequence of trades below:

1. Borrow USD for, say, 30 days, at rate $r_{t;\$}$ directly in USD money markets
2. Sell USD against EUR spot to obtain $1/S_t$ euros; simultaneously enter a forward contract F_t, reversing the currency exchange at a predetermined price in 30 days (effectively entering a FX swap contract),
3. Invest the EUR-denominated funds at the currently available 30-day euro rate $r_{t;\star}$ in EUR money markets.
4. At maturity, repay the USD debt, $(1+r_{t;\$})$.

The (zero-profit) no-arbitrage condition defines the relation known as CIP. A requirement is that all transactions (borrowing, spot, forward and lending) are made simultaneously and hence the profits are known ex-ante (we therefore drop time subscript henceforth). The forward contract removes the FX risk, and, if the interest rates in the investment leg are risk-free, this will amount to a risk-free (self-financed) arbitrage trade. In actual implementations, the spot-forward combination will be replaced by an FX swap contract since the swap market is more liquid than the (outright) forward market (e.g. BIS, 2016) (see Online Appendix for further details).

It is also quite common to refer to the profits from the above sequence of trades as the *cross-currency basis*, defined as follows:

$$Basis = \frac{F}{S}(1+r_{\star}) - (1+r_{\$}), \tag{1}$$

[8]Here we take a funding perspective of LOOP (sometimes also referred to in the literature as "borrower's arbitrage"). Alternatively, one can take an investment perspective by comparing the investment return in currency B with that on a synthetic asset (i.e. the implied investment return based on currency A hedged back into currency B).

that is, the discrepancy between the synthetic interest rate implied by the FX swap market $\frac{F}{S}(1+r_{\star})$ and the direct interest rate $(1+r_{\$})$. A higher reading of the basis, as defined here, thus corresponds to a situation where the USD trades at a premium in the swap market compared to raising funds directly in U.S. money markets.[9]

Accounting for bid-ask spreads. One component of the costs in arbitrage trades comes from bid-ask spreads. In the example above, the arbitrageur will borrow at ask rates, lend at bid rates, buy spot at ask (euro is the base currency in dollar-euro exchange rate), and sell forward at the bid. Taking bid-ask spreads into account, CIP arbitrage is *not* profitable under the following conditions:

$$\left(1+r_{\$}^{a}\right) \geqslant \frac{F^{b}}{S^{a}}\left(1+r_{\star}^{b}\right), \tag{2}$$

$$\left(1+r_{\star}^{a}\right) \geqslant \frac{S^{b}}{F^{a}}\left(1+r_{\$}^{b}\right), \tag{3}$$

where the superscripts a and b symbolize ask and bid rates, respectively, and $r^{a} > r^{b}$.[10] The equations simply state that for no-arbitrage to hold, the borrowing rate (ask) has to be equal or higher than the implied lending rate in the same currency.[11]

However, as shown in the recent literature (e.g. Du, Tepper, and Verdelhan, 2018) bid-ask spreads alone cannot explain why the cross-currency basis has been different from zero in the post-crisis period.[12] As we argue in this paper, it is of first-order importance, though, to adequately capture the *level* of the funding cost in the arbitrage strategy. We now turn to this critical choice.

[9]We prefer to define the basis this way, given the more straightforward link to arbitrage strategies borrowing directly in USD funding markets. Note that other papers sometimes define the basis the other way around (e.g. Du, Tepper, and Verdelhan, 2018).

[10]See Appendix B and the Online Appendix for further details on measuring CIP violations, respecting all market conventions.

[11]For LOOP deviations, the equations are similar, except that the interest rates are considered at the same prices, bid for lending comparison and ask for borrowing comparison. For details, see Akram, Rime, and Sarno (2009).

[12]See also Figure OA.1 and Table OA.IV in the Appendix where transaction costs are appropriately taken care of. Simple comparison of deviations with and without bid-ask spreads reveal that spreads can only explain about 2-5% of total deviation.

2.2. *The choice of money market rates in analysis of CIP arbitrage*

Unlike in the textbook description of CIP, there is a plethora of money market rates faced by different types of market participants and with very different characteristics.[13] As shown by Duffie and Krishnamurthy (2016), the dispersion across different types of rates has increased substantially post-crisis. Against the backdrop of structural changes in funding markets, care needs to be exercised to select rates that most adequately capture the marginal funding costs of the critical arbitrageurs in international money markets (i.e. global banks).

Global banks are the main arbitrageurs due to their unique role and flexibility in financial markets. Other important market participants, e.g. hedge funds, are less likely to engage as major arbitrageurs. To arbitrage price dislocations, hedge funds are dependent on bank/prime broker funding (see, e.g., Moore, Schrimpf, and Sushko, 2016). Banks generally avoid charging their customers below their own funding cost and hence would be reluctant to provide hedge funds with the leverage to profitably exploit any CIP deviations.[14]

The funding leg of CIP arbitrage. In the earlier literature, it used to be common to rely on an interbank rate (such as LIBOR) when studying the validity of CIP. Since unsecured interbank markets are no longer a vibrant source of term funding for banks (with LIBOR even at the risk of potential discontinuation for that reason), it is paramount to capture the funding costs from wholesale funding sources other than banks. Figure 1 shows that the activity in U.S. interbank markets has decreased after the GFC, making interbank borrowing no longer a viable source for short-term funding for banks.[15]

[Insert Figure 1 about here]

In the post-GFC world, money market instruments such as Commercial Paper (CP) or Certifi-

[13] Table A.1 in Appendix A gives an overview of our data.

[14] In contrast to leveraged investors like hedge funds, real-money asset managers (e.g. pension funds, reserve managers or sovereign wealth funds) can be considered to be long-only investors. While their search for cross-border value in investment options may also respond to pricing in the FX swap market, such opportunistic behavior cannot be regarded as arbitrage in the strict sense as it does not involve a full (self-financing) roundtrip.

[15] These developments can be traced to two main drivers as described in Schrimpf and Sushko (2019): (i) changes in banking regulation, and (ii) the abundance of central bank reserves due to QE policies. Similar trends can be observed in other currency areas, see e.g. the ECB's money market survey (ECB, 2015).

cates of Deposit (CD) have emerged as the key sources of unsecured wholesale term funding for banks. Such funding vehicles are issued by financial and non-financial corporations. CPs are issued with maturities up to 9 months, while CD maturities can also be longer. These instruments are typically held by non-banks, such as money market funds or other institutional investors, and provide a flexible way for banks to attract short-term unsecured funding. There is substantial heterogeneity across banks' funding costs in CP and CD markets. High-rated banks (A-1/P-1 rating) pay significantly less for USD funding than so-called mid-rated banks (A-2/P-2 rating) or lower-rated banks.[16]

CD issuance is subject to the requirement that the issuing bank be located in the U.S., either by subsidiary, branch or head office. We collect all USD CD issuances with maturity close to 1-month, 3-month and 6-month maturity, giving us a large cross-sectional variation in funding rates. However, this comes at the cost of slightly fewer time series points as we only have data from issuances. For our analysis of arbitrage profits, we hence primarily use the CP rates for which we have a more complete time series. However, we exploit the granularity of the CD data by looking at the dispersion in funding costs across institutions and the relationship between issuance volume and USD funding cost. The dataset (obtained from Bloomberg) includes CD issuances by most of the major global banks, with precise information on the date of issuance, volume and yield when issued. After filtering out non-rated small banks (mostly local U.S. banks), and aligning our sample with the rest of our analysis (January 2013 - June 2017), we are left with around 17,000 observations.

Comparison with other money market rates. Some words on money market rates that *do not* provide an accurate reflection of arbitrageurs' marginal funding costs are also in order. For the sake of comparison, we also consider interbank offered rates (IBOR), individual quotes of interbank deposit rates, and Overnight Indexed Swaps (OIS) in this study. Interbank deposit rates are quotes by a selection of banks indicating the price at which they are willing to lend and borrow cash to/from another bank on an unsecured basis. Such non-binding quotes are taken into consideration when panel banks give their submissions in the LIBOR survey. As highlighted above, we do not

[16]Results for the best rating group, A-1+/P-1, are qualitatively similar to the results of A-1/P-1 and available on request. We leave out this group for reasons of space and because it is a narrower set of banks with fewer observations. Figure OA.2 in the Online Appendix compares results for A-1/P-1 banks to A-1+/P-1 banks. We refer to A-2/P-2 banks as mid-rated as there are many banks with international operations with a lower rating (or no rating at all).

consider these rates to be an accurate reflection of banks' marginal funding costs in the post-GFC environment.

In a similar vein, we also do not deem OIS or repo rates to be suitable for the analysis of a no-arbitrage relation like CIP. OIS contracts are derivatives and not easily used for raising funds.[17] To obtain funding at the OIS rate, the arbitrageur has to roll over funding overnight, implying substantial funding liquidity risk. Since OIS rates are regarded as proxy for risk-free rates, they are insensitive to fluctuations in term funding liquidity premia and thus cannot represent the *marginal* funding costs of the typical arbitrageurs when funding conditions change.

Similar issues apply to repo rates. Raising funds through a repo encumbers high-quality collateral such as a U.S. Treasury security, which needs to be funded unsecured (or by equity) in the first place. A cross-currency trade financed by a repo also assumes that the arbitrageur receives collateral in the investment leg of the transaction. However, equivalent to differences in unsecured funding costs across currencies, the shadow cost of the collateral varies across currencies. This means that if the shadow cost of the collateral encumbered in the funding currency is higher than the shadow cost of the collateral received in the investment currency, this difference in shadow cost of the collateral is not captured in the repo rate and has to be accounted for.[18] Hence, we do not deem repo rates to be suitable to capture arbitrageurs' marginal funding costs. We provide a more detailed analysis of trading strategies involving both OIS and repos in the Online Appendix.

Descriptive statistics for the CP, interbank deposits and IBOR rates over OIS rates are reported in Table 1 (Table OA.I in the Online Appendix shows the same descriptive statistics for 1-week and 1-month maturity). Unless otherwise stated, we focus on the post-crisis period from the beginning of 2013 (after both GFC and the Euro crisis), a period of fairly calm financial markets, where explaining FX swap market developments has proven particularly challenging. From Table 1 we see that both the level and the variation of the money market spreads differ quite a lot across the different rates. Together with the structural changes in money markets, as e.g. seen in Figure 1, it

[17] An OIS contract is an interest rate swap exchanging a fixed interest rate against a pre-defined floating overnight rate. Since the overnight rate under normal circumstances contains a negligible credit risk premium (due to the very short term) and a majority of central banks target the overnight rate, this rate is usually close to the key policy rate. An OIS contract does not involve any exchange of the principal (as it is a derivative), only the net difference between the realized overnight rate during the term of the contract and the agreed fixed rate.

[18] Kohler and Müller (2018) illustrate this point by using repo rates on collateral in *same* currency, hence removing the difference in the shadow cost. They find a significant drop in their measures of CIP deviations.

becomes clear that the choice of money market rates matters.

[Insert Table 1 about here]

The investment leg of CIP arbitrage. For proper implementation of arbitrage, it is important to make sure that the investment vehicle is close to risk-free.[19] After all, the main economic prediction of CIP is that riskless arbitrage profits from borrowing and investing in international money markets and FX swap markets should be zero (once the relevant costs have been accurately controlled for). We hence deviate from prior work on CIP by considering an interest rate for the investment leg of the arbitrage trade that differs from that for the funding leg.

As risk-free investments, we turn to government T-bills (bid quotes) and central banks' (CB) deposit facilities. The main difference between the two instruments is that the former is widely accessible to all market participants, whereas the latter is only available to eligible counterparties of the central bank. Moreover, the CB deposit rate is in most cases unresponsive to the amount of reserves placed in the facility.[20] By contrast, T-bill rates fluctuate with changes in demand and supply conditions. Table OA.II in the Online Appendix provides descriptive statistics for the risk-free investment vehicles.

Maturities, swap order flow and time-variation in money market spreads. We consider three different tenors: 1-week, 1-month and 3-month (with special emphasis on the 3-month tenor unless there are important lessons to be made from the short tenors). These tenors are the most liquid and natural choices to implement CIP arbitrage. Our study comprises the set of most liquid currencies worldwide, that is, Australian dollar (AUD), Canadian dollar (CAD), the euro (EUR), British pound sterling (GBP), Japanese yen (JPY), and Swiss franc (CHF), all quoted against the U.S. dollar (USD).

Banks may turn to the FX swap market in order to try to benefit from low funding costs in foreign currency, or try to exploit CIP arbitrage violations. From our high-frequency data from

[19] Needless to say, lending rates to other banks do not fulfil this criterion. Academic work on CIP deviations prior to the GFC often considered unsecured rates such as IBOR for the investment leg of CIP arbitrage trades – a perspective which is not warranted due to credit risk.

[20] In cases where the central bank has adopted a tiered deposit remuneration schedule (Bech and Malkhozov, 2016), we use the lowest rate as an expression of the marginal rate of remuneration. The more favorable rates only apply to a restricted cash amount.

the Reuters D3000 platform (similar to the electronic limit order book for FX spot), we match transaction prices with bid and ask prices to infer if the initiator of the transaction was buying USD or selling (at the spot leg). From this we create a daily measure of swap market order flow as the net of USD buyer-and seller-initiated volume at the spot leg of the swap.[21] We are, to the best of our knowledge, the first paper to study the impact of order flow on intermediaries' FX swap market quotes.

Figure 2 presents 3-month CP and CD rates, above the 3-month OIS rate. All spreads are positive, while the volume-weighted CD rates are more volatile. The vertical line marks the implementation of the U.S. Money Market Fund (MMF) reform on October 14, 2016, which effectively led money market funds to fund less of banks' short-term debt (see Figure 1b).[22] Both for high- and mid-rated banks, the spread to OIS was rising in anticipation of the implementation of the U.S. MMF reform. In this adjustment phase, the shrinkage of prime funds' assets under management led to a worsening of USD funding conditions, especially for foreign banks. Panel (b) shows that around the time of the MMF reform, the CP-OIS spread increased similarly for both high- and mid-rated banks in the U.S., and not so in other countries suggesting strained funding liquidity conditions in USD markets. Figure OA.2 in the Online Appendix presents CP-OIS spreads for other currencies and longer samples. These figures show a significant compression in wholesale funding costs especially in EUR, CHF, and JPY when the central banks of the respective currency areas significantly expanded the supply of reserve balances as a by-product of their balance sheet policies.

[Insert Figure 2 about here]

[21] Akram, Rime, and Sarno (2008) analyzed high-frequency on pre-GFC data. In the post-GFC regime, and using daily interest rates, a daily frequency is sufficient. Analysis of high-frequency swap rates gives similar results and is available upon request.

[22] The U.S. MMF reform induced two main changes to the industry which made prime funds much less attractive for investors: i) a requirement to publish mark-to-market values of assets in contrast to the constant asset valuation previously used, and ii) a possibility for the fund to impose a redemption fee of 2 per cent if the assets that can be liquidated within one week fall below 30 percent of the fund's assets or stop all redemptions for up to 10 days if the threshold of 30 per cent is breached.

3. Law of one price violations and CIP arbitrage

We now turn to our empirical study of LOOP violations and CIP arbitrage profits in international money markets. In line with the main focus of our work, our analysis in the following primarily relies on money market rates that are consistent with the marginal funding costs of the main arbitrageurs, i.e. globally active banks. The analysis allows us to assess which types of banks are in a position to reap economically significant arbitrage profits, and which are not.

3.1. LOOP violations in international money markets

As discussed above, LOOP deviations give rise to opportunistic behavior, e.g. to either directly borrow funds in the target currency, or to fund in USD and swap into the target currency, depending on what is more attractive in terms of cost. Previous research shows that in the post-GFC world, the relevant arbitrage case has been to directly raise USD and swap into foreign currency (except for AUD. See Table OA.IV in the Online Appendix for all currencies). Hence, we will focus on this particular case only in the following.

[Insert Figure 3 about here]

Figure 3 illustrates that the choice of interest rates is crucial when analyzing LOOP violations.[23] It shows box plots for the LOOP violations, over the post-crisis period (after 2013), averaged across the three currency pairs for which we have CP rates (EUR, JPY and GBP, against USD). We distinguish between four different money market rates: OIS, IBOR, interbank deposits, and CP rates (averaged across rating categories). Crucially, these rates differ by how they capture marginal funding costs. For OIS and IBOR rates, we observe economically significant LOOP violations (vertical line inside bar) of around 15 basis points or higher on average over the post-crisis period.

However, the main takeaway from Figure 3 is not that there are some LOOP deviations for certain interest rates (as also previous research has shown), but that LOOP violations are significantly

[23] See Tables OA.VI – OA.VII and Figure OA.3 in the Online Appendix for other maturities and for separate currencies.

lower for interbank deposits and basically non-existent for CP rates.[24] A preliminary interpretation (further developed in Section 4 below) is that price signals from CP markets serve as an important ingredient when swap market intermediaries set FX swap quotes.

The main reason why violations using CP rates are small is that CP rates — unlike some of the other money market rates — appropriately reflect banks' marginal funding cost. The unsecured marginal funding cost of bank j in USD, $r_{j;\$}$ (suppressing the t subscript), can be expressed as:

$$r_{j;\$} = r^f_\$ + cr_j + \widetilde{lp}_\$, \tag{4}$$

where $r^f_\$$ is the USD risk-free rate, cr_j denotes a compensation for credit risk (assumed constant across currencies for global banks) and $\widetilde{lp}_\$$ stands for the liquidity premium in USD.

Illustrating the role of funding liquidity premium differentials. It is worth illustrating the importance of funding liquidity premia based on a simple proxy. First, we insert the OIS rate as a proxy for the risk-free rate in (4), and, second, assume that the credit component faced by a particular bank j is the same across currency areas. Taking the difference in the marginal funding spread $(r_j - r^{OIS})$ across the two currencies will then filter out the credit component and give us a measure of the *relative* liquidity premium differential

$$\widetilde{lp}_\$ - \widetilde{lp}_\star = \left(r_{j;\$} - r^{OIS}_\$\right) - \left(r_{j;\star} - r^{OIS}_\star\right), \tag{5}$$

between USD and the foreign currency. This simple measure can be averaged over bank-specific data, or, as we do, over CP-spreads for different rating categories, to minimize noise.

For ease of reference, we also define the cross-currency basis computed from OIS rates (in short "OIS-Basis") as follows

$$\textit{OIS-Basis} = \frac{F}{S}\left(1 + r^{OIS}_\star\right) - \left(1 + r^{OIS}_\$\right). \tag{6}$$

[24] A main reason why violations based on interbank deposits are so small, compared to IBOR rates, is that quotes of interbank deposits capture how banks are pricing funds internally, a common practice called Funds Transfer Pricing (FTP). This important institutional feature is discussed in the Online Appendix.

Figure 4 illustrates that funding premium differentials (between the USD and other currencies) and the OIS-Basis are highly correlated. In Panel (a) the blue line shows the time series of the OIS-Basis (positive number suggests deviation) together with the liquidity premium differential vis-à-vis the USD in red (both averaged across currencies). The latter is constructed based on CP rates following Equation (5) outlined above. Panel (b) depicts the cross-plot of the cross-currency basis with OIS rates and the average liquidity premium differential across currencies vis-à-vis the USD.

[Insert Figure 4 about here]

The fact that proxies for the relative funding liquidity premium exhibit fluctuations that closely resemble those in the OIS-Basis indicates that funding strains in USD markets are a primary driver of both the premium to obtain USD in the FX swap market and funding spreads in U.S. money markets. The vertical line again marks the implementation of the MMF reform, and both series have their peak around this event and fluctuate quite closely together (liquidity premium differential on inverse axis on the right). Figure 1b above illustrates the large decline in assets under management by prime funds prior to the implementation date and the corresponding decline in CP issuance volume by foreign financial institutions. MMFs have traditionally been the marginal investor in CP issued by banks. The change in their investment strategy caused USD funding disruptions for banks reliant on CP funding.

What this boils down to is that OIS based LOOP violations largely reflect fluctuations in the *relative* difference in term funding liquidity premia across two currencies. Based on this interpretation, a widening of the OIS cross-currency basis is not necessarily an indication of arbitrage profits, but merely suggests that the costs of USD term funding (relative to other currencies) have firmed.[25] When considering marginal funding rates such as CP rates, though, LOOP violations are relatively minor.

[25] Using an OIS for arbitrage purposes (implicitly) assumes a highly complex sequence of trades. This mechanism is illustrated in Figure OA.9 in the Online Appendix. The Online Appendix also discusses how an OIS based arbitrage exposes the arbitrageur to roll-over risk.

3.2. *CIP arbitrage in international money markets*

We now turn to our main analysis of arbitrage strategies in international money markets. The textbook version of CIP states that riskless arbitrage profits from borrowing and lending in international money markets, covering the FX risk through a derivatives transaction, should not lead to any economically relevant profits (after accounting for the relevant costs). But, how to set up a *riskless* CIP strategy in practice? To answer this question, it is important to take the perspective of a globally active bank and to account for the relevant costs it faces when setting up a CIP arbitrage trade. For simplicity, our analysis in the following considers only arbitrage trades with direct borrowing in USD markets and swapping into foreign currency as opposed to the other direction (given that the latter is not a profitable strategy. See e.g. Table OA.IV reported in the Online Appendix).

An important distinction pertains to the funding and the investment leg of the arbitrage trade. For the funding leg, we use CP rates as these provide us with realistic marginal funding costs for banks in the post-crisis market environment as discussed above. As vehicles for the investment leg, we consider *risk-free* instruments: (i) short-term government paper (T-bills), and (ii) central bank deposit facilities. These choices are in line with the basic requirements for arbitrage, namely that the investment be risk-free and implementable in practice. Moreover, these types of risk-free trades bind little to no capital for banks.[26]

Given the evidence above, we split the post-crisis sample into the period before and after the U.S. Money Market Fund (MMF) reform. Although the MMF reform came into effect October 14, 2016, Figures 1b and 2 above show that large adjustments took place in anticipation of the reform. Thus, we determine the start of the MMF reform period to be April 2016. The transition phase is a particularly interesting sub-sample and nicely illustrates changes in USD funding liquidity premia.

[Insert Table 2 about here]

[26]The statement that a risk-free trade does not consume any capital may not be entirely correct in presence of Funding Value Adjustment (FVA), Credit Value Adjustment(CVA) and Leverage Ratio Andersen, Duffie, and Song (2019); Duffie (2018). However, in this paper we are considering short-term trades (up to 3 months), which are much less affected by FVA and CVA. The FVA increases with the probability of default and loss given default. The shorter the maturity of the funding, the lower is the probability of default. Two-way Credit Support Annex (CSA) agreements, which are common among major market participants, significantly reduce both CVA and FVA in the FX swap. Only U.S. and UK banks have been subject to Leverage Ratio requirements during our sample period.

Table 2 Part I covers the first sub-sample, while results for the MMF reform sample are presented in Part II.[27] The left-hand panel shows CIP arbitrage profits with central bank deposit facilities as investment vehicle, while the right-hand panel of the Table reports profits when the funds are invested in T-bills. First, we consider USD funding costs by lower-rated (A-2/P-2) banks in the CP market, swapped into foreign currency and invested into the T-bill in the respective currency. Note that these banks (while being rated some notches below high-rated banks in their CP issuance) can still be considered as fairly creditworthy institutions, relative to many other financial institutions that do not have access to the CP market in the first place. Panel A of Table 2 shows that during the first sub-sample hardly any arbitrage profits can be reaped for A-2/P-2 banks. For better-rated banks (Panel B), there are some arbitrage profits for investments in CHF- and JPY-denominated T-bills.

Table 2 (left-hand panel) reports CIP arbitrage profits when global banks borrow in USD CP markets and place the swapped funds in foreign central banks' deposit facilities. Panel A of the Table shows that in the CHF and the JPY some arbitrage profits have been available even for A-2/P-2 banks. These are fairly small in economic terms, though, around 1 and 4 basis points on average over the post-crisis sample period up to the U.S. MMF reform. For the set of high-rated global banks with good access to funding in USD markets (Panel B), the profits have generally been larger, with economically viable arbitrage opportunities as large as 14 basis points in JPY and CHF.

It is striking that arbitrage profits involving CB deposit facilities are much larger than when investing in T-bills. It is important to keep in mind that the rate of remuneration offered on central bank deposits is insensitive to the volumes placed in the facility. And markets are segmented in that only a selected group of financial institutions has access to the deposit facility. The rate of remuneration of excess reserves thus is unlikely to act as a solid anchor for pricing in the FX swap market at all times. On the other hand, the pricing of T-bills adjusts to demand and supply imbalances. If a cross-border arbitrage opportunity combining an FX swap and T-bills emerges, one would expect both the FX swap price and the T-bill rate to respond to the corresponding arbitrage induced flow.

Figure 5 shows time series of CIP profits involving CP funding and invested in either Treasury

[27] See Table OA.VIII in the Online Appendix for other maturities.

bills (Panel a) or central bank deposit facilities (Panel b). We average over EUR, CHF, and JPY in order to highlight the cases with positive CIP profits, as evident from Table 2 above, and use a two-week moving average for visibility of trends.[28] CIP profits funded by CP issuances are in all cases much smaller than the OIS-Basis and both for high-rated and mid-rated banks that invest in Treasury bills, there are few periods with positive CIP arbitrage opportunities.

Panel (b) in Figure 5 reveals some prolonged periods with profitable CIP arbitrage opportunities in EUR, CHF, and JPY when central bank deposits are used as the investment leg. Profits trend up ahead of the implementation of the MMF reform of October 2016. In fact, during the period of asset contraction in U.S. prime money market funds, median CIP arbitrage profits available to high-rated banks were as high as 30-40 basis points, as shown in Table 2 Part II. This is however much lower than the 80-100 basis points suggested by the OIS-Basis.

During this episode of strained USD funding conditions, even lower-tier banks have faced economically attractive arbitrage opportunities, with riskless profits as high as 26 basis points on average (in case of deposits with the Bank of Japan). Needless to say, however, a pre-requisite for reaping such profits has been to maintain access to wholesale non-bank USD funding markets over this challenging episode of falls in issuance volumes and assets under management for U.S. prime MMFs (see Figure 1b). Furthermore, as we will see below, the supply of short-term funding is quite elastic, in that increased volume will also lead to a pick-up in the funding costs.

[Insert Figure 5 about here]

A natural reaction when presented with evidence of arbitrage is that some prices are measured incorrectly. Given our careful choice of interest rates one might ask dealers may embed a risk premium in the FX swap price to guard against counterparty risk. We are using FX swap prices from the interdealer market. In the interdealer market, the use of two-way Credit Support Annex (CSA) agreements are common practice, meaning that both counterparts are obliged to pay variation margin according to movements in the FX swap price. This effectively eliminates counterparty risks and is the reason for negligible price differentiation in the interdealer market.[29] As a consequence, the FX swap prices used in this paper are the most appropriate to use for a arbitrageur.

[28] Figure OA.4 in Online Appendix shows that when averaging over AUD, CAD, and GBP, CIP seems to hold as profits are primarily negative.

[29] There are larger price differentaion in the end-user segment.

Interim summary. The following lessons can be drawn from the analysis above: (i) deviations from CIP are either non-existent, or an order of magnitude smaller when using marginal funding rates such as CP rates rather than e.g. OIS rates; (ii) for a large set of banks, either facing a lower rating or without access to the relevant central bank deposit facilities, a non-zero cross-currency basis when calculated from OIS rates does not imply economically viable arbitrage opportunities; (iii) during periods of liquidity strains in the USD market, as in the asset contraction period prior to the implementation of the MMF reform, CIP arbitrage opportunities were sizeable for those institutions that retained market access. We now turn to a framework that can help us understand these empirical observations.

4. FX swap market equilibrium

The analysis in the previous section begs a key question: How is it possible that risk-free arbitrage profits for a narrow set of banks can persist over such an extended period of time? To tackle this question, it is important to study the challenges faced by an FX swap intermediary in matching the flows of different market participants.

Compared to the situation of no-arbitrage prior to the GFC (e.g. Akram, Rime, and Sarno, 2008), three major forces have altered the FX swap market equilibrium in the post-GFC environment: (i) substantial heterogeneity in USD funding costs across banks; (ii) the abundance of central bank reserves (as a by-product of QE) has affected funding liquidity premia differently across major currency areas; (iii) limited scope for individual banks to scale the arbitrage, in particular due to quantity constraints affecting the price elasticity of the supply of USD.

These forces create opportunities for banks, either for obtaining cheaper USD financing or exploiting arbitrage. Below we discuss how an FX swap market maker can respond to changes in relative funding liquidity premiums, and in fact use his quote-setting behavior in such a way as to induce arbitrage flows in order to obtain a balanced order flow. We argue that quoting prices that imply arbitrage opportunities, and that are traded upon, can be part of an equilibrium. Such an equilibrium can only be sustained if arbitrage positions are not infinitely scalable. Hence, after discussing the equilibrium in the FX swap market, we present empirical evidence supporting our framework.

4.1. *Divergence in funding liquidity premia*

A key implication of unconventional policies implemented since the GFC has been that funding liquidity premia evolve differently across currency areas (See Figures 4 and 2 above and Figure OA.2 in the Online Appendix). This in turn has made it significantly more difficult for intermediaries to quote an FX swap rate so that the law of one price holds for all money market rates at the same time. To see this, consider the following equation (based on Equation (4))

$$\frac{F}{S} \approx \frac{1 + r^f_\$ + \widetilde{cr}_\$ + \widetilde{lp}_\$}{1 + r^f_\star + \widetilde{cr}_\star + \widetilde{lp}_\star}. \tag{7}$$

Prior to the GFC and central banks' reliance on unconventional policies, liquidity premia $\widetilde{lp}$ (for different currencies) were relatively small and roughly equal across currencies. If credit premia $\widetilde{cr}$ (for equally risky banks) were similar across currencies, the same F/S could ensure LOOP for different interest rates (or credit premia).

Figure 6 sketches four possible states of the FX swap market. Panel (a) illustrates how in, such a normal market environment, a single swap rate can maintain the law of one price (LOOP) for different funding rates. The two vertical lines indicate interest rate levels in the two countries ("U.S." on the left-hand side and "Foreign" on the right-hand side). For simplicity, we look at three levels of funding rates faced by different banks in the credit spectrum (top, mid, low) as indicated on the vertical axis. The slope of the curve connecting interest rates in the two currency areas is the FX swap market implied interest rate differential (as given by the F/S-ratio). If the vertical distance between the different interest rates is the same, e.g. when risk premia are aligned for equally risky banks, LOOP will hold for all levels of funding rates with just one swap rate (the F/S-ratio). The absence of any LOOP deviations is indicated by marking the curve with zeros.

[Insert Figure 6 about here]

Now consider the case of a divergence in liquidity premia across currency areas. A main reason behind such a divergence can be a large rise in the supply of reserve balances, in turn leading to a compression in marginal funding costs of banks domiciled in the corresponding QE economies. In Figure 6 we assume that this leads to a drop as low as to the rate of remuneration of the central bank deposit facility. Banks at the bottom of the credit spectrum benefit disproportionately from the fall in short-term funding costs. An improvement in the availability of funding is akin to a fall in liquidity premia, $\widetilde{lp}_{\star}$ in Equation (7). The empirical evidence in Section 3 showed that relative funding liquidity premia have evolved differently across major currency areas: USD liquidity premia, $\widetilde{lp}_{\$}$, have typically been elevated, in large part due to structural demand for USD funding by non-U.S. domiciled global banks, whereas funding liquidity premia dropped in other currencies where central banks supplied ample liquidity to the market as a result of their balance sheet policies.

Panel (b) of Figure 6 illustrates the impact of a compression in banks' marginal funding costs in one currency area, while those in USD remain elevated. The previous bank-specific marginal funding costs in foreign currency, now in italics, are no longer binding in this situation. Instead, the rate of remuneration of the CB deposit facility has become the effective marginal funding rate for all banks (irrespective of credit-rating).[30] The Figure shows that in this situation it is impossible for an intermediary to quote a single FX swap rate to be consistent with LOOP (or CIP) for the key money market rates faced by all banks in the credit spectrum.

The difference in funding liquidity premia is partly due to the special role of USD in the global financial system as the primary invoicing, funding, investment and settlement currency in the world (see e.g., Gopinath and Stein, 2018; Eren and Malamud, 2018). The U.S. money market is by far the largest and most vibrant in the world and globally oriented non-U.S. banks tap this market as the access to retail deposit funding in USD might be limited (due to lack of local presence and tax purposes for instance). However, these global banks have ample access to deposit funding (and potentially central bank funding) in their home currency. Their enduring USD demand to finance US dollar banking assets which can either be funded by directly raising USD or local currency funding swapped into USD. When money market funding becomes more difficult to obtain, global banks resort to the FX swap market to fill the gap. However, a large share of deposit-rich US banks is domestically oriented and hence will refrain from provide USD in the FX swap market.

[30]The main reason is that banks awash with holdings of reserve balances, rather than obtaining market funding, can simply run down their holdings of reserves. Hence, the rate of remuneration of reserves held at the foreign central bank's deposit facility determines funding costs at the margin.

4.2. *Implications for intermediaries and order flow in the FX swap market*

What does this imply for the behavior of key intermediaries, i.e. bank dealers that make markets in FX swaps? When an FX swap dealer enters into a transaction with a counterparty, she/he has three alternatives: (i) attract an opposite interest (matched flows); (ii) fund the delivery of the currency as short as possible and invest the currency received until opposite interest is found, which involves taking on some (short-term) liquidity risk; (iii) fund the open position at the same maturity as the FX swap and invest at the same maturity. A market maker typically has a strong preference for the first option. This is further reinforced by internal overnight risk limits that effectively force the market-making desks to end the day "flat."[31]

In the environment described above, any quote of FX swap points set by the dealer will imply a profitable opportunity for at least one set of swap end-users. Imagine a situation where the dealer quotes prices (i.e. swap points) such that the implied rate differential equals that between the USD rate faced by high-rated banks and the foreign central bank's deposit facility rate.[32] It is clear that such a quote cannot be an equilibrium rate because all banks with more costly direct funding in USD could obtain dollars more cheaply via the swap-market. The market maker would face highly one-sided demand pressure for USD (indicated by arrows that point towards USD for the spot leg of the swap) and would accumulate a large inventory.

To be consistent with equilibrium, the quotes of the market maker thus need to induce flows in both directions. This is accomplished by setting the swap quote so as to imply an interest rate differential such that LOOP holds for the majority of banks that account for the bulk of USD demand.[33] Similarly as above (Panel (b)), banks with higher USD funding costs have an incentive to obtain dollars via the swap market (i.e. a response to a LOOP deviation).

This new equilibrium in FX swap markets induces opposite flows by granting a CIP arbitrage opportunity to those few banks with advantages in terms of USD funding costs. Their low USD

[31] According to conversations with market participants, a swap desk is commonly seen as having failed if it ends up with a non-matched book and will need to turn to banks' internal capital markets for funding. To disincentivize such a situation, it is common for the banks' Treasury department to provide such funds at a penalty rate.

[32] In Panel (b) of Figure 6, this case is indicated by the red dashed line connecting the foreign CB rate and the low U.S. rate, marked with zeros to indicate no deviation from LOOP for the high rated banks (and hence no CIP arbitrage).

[33] This is indicated by the solid red line marked by zeros in Panel (c) of Figure 6, connecting USD rates for mid-tier banks with the rate on the foreign central bank's deposit facility. Note that this quote implies a slightly steeper FX swap-implied rate differential than the non-optimal alternative ('dashed' line).

funding rates render it economically attractive to borrow in unsecured USD markets, swap the dollars into foreign currencies and place the funds with foreign central banks (or other risk-free instruments, e.g. T-bills). The implied flows supporting this as an equilibrium are shown in Panel (d) of Figure 6 as arrows in both directions.

4.3. *Empirical evidence*

We now turn to an empirical investigation of the predictions generated by the framework outlined above. First, we show that the pricing in FX swap markets responds to swap order flow in a way consistent with our framework, suggesting that dealers revise their quotes to avert inventory imbalances. Second, we present evidence that highly rated banks, but not lower-rated ones, do in fact take advantage of the arbitrage opportunities involving central bank deposit facilities. For this situation to be consistent with an equilibrium, such arbitrage opportunities for highly rated banks must be bounded, though. Thus as a third step, we present evidence of upward-sloping USD supply curves based on issuance data in the USD CD market, suggesting that potential arbitrageurs face limits to scaling up their positions.

FX swap market imbalances: the role of swap order flow. As outlined above, swap market makers have a primary incentive to quote FX swap points so that (in expectation) they face a balanced order flow from end-users. Possible imbalances, however, can arise, for instance in a situation of severe funding constraints in the market for USD, when lower-tier banks need to turn to the swap market to raise USD. Such imbalances will be associated with movements in swap order flow, i.e. flow into USD at the spot leg. Faced with such a situation, the swap dealer will have to quote a higher swap rate $F - S$, i.e. a steeper curve in Figure 6, in order to attract a matching flow of opposite sign. As outlined above, this flow will come from less constrained banks in the USD market (i.e. highly rated banks), who are in a position to supply USD to the swap market. Consequently, our framework predicts that a CIP arbitrage opportunity (a positive CIP deviation) will arise for highly rated banks in response to a positive order flow imbalance.

To test this, we rely on panel regressions of the form

$$\Delta CIP^{dev}_{i,t} = \alpha_i + \gamma \cdot CIP^{dev}_{i,t-1} + D_{i,t} \cdot \beta_{swapOF} OF^{swap}_{i,t} + D_{i,t} \cdot \beta_x X_{i,t} + \varepsilon_{i,t}, \tag{8}$$

where we regress the change in CIP deviations for our six currencies onto a measure of FX swaps order flow $OF^{swap}_{i,t}$, and a set of control variables $X_{i,t}$. Order flow is standardized and measured so that a positive number represents flow into USD at the spot leg and into foreign currency at the forward leg. The regression also includes the lagged level of CIP deviation to capture the forces pulling any deviations back to zero (akin to an error-correction mechanism). All variables capturing the dynamics are interacted with dummies $D_{i,t}$ indicating whether there is a deviation or not. This allows us to capture that variables most likely have a different impact during periods of arbitrage opportunities than in more normal periods. As an extra control variable we use a broad spot FX USD index, as suggested by Avdjiev, Du, Koch, and Shin (2018), where positive changes indicate a USD appreciation.[34]

[Insert Table 3 about here]

Table 3 presents regression results for 3-month arbitrage profits involving CB deposits as investment vehicles (given less scope for arbitrage using Treasury bills).[35] For each case, CIP arbitrage profits are computed based on CP funding costs by mid-tier (A-2/P-2) and highly rated banks (A-1/P-1). We find that the coefficient on swap order flow is positive and significant in all regressions, confirming the intuition of our framework. A positive coefficient on the order flow variable suggests that the demand pressure to obtain USD via swaps, or in more technical terms, flow pressure to obtain USD at the spot leg of the swap (while buying foreign currency forward), requires an increase in the CIP deviation.

The magnitudes of the estimated coefficients suggest that the price impact of order flow varies depending on how severe CIP deviations are. Interacting order flow with a CIP dummy shows that in orderly markets, with no deviation, only a small quote update of 0.2bp, for a one standard

[34] Alternative specifications, such as adding bilateral spot exchange rates, spot FX order flow, and our measure of liquidity premium differentials as control variables, are summarized in Figure OA.5.

[35] Table OA.IX in the Online Appendix shows results from fixed-effect panel regressions for all maturities and the Money Market Fund reform sample.

deviation change in flow, is needed to curb an order imbalance. During periods when deviations are observed for A-1/P-1 banks, a positive order flow imbalance signals a worsening of funding conditions in USD money markets to the swap dealer. In this case, the dealer may expect further demand pressure from lower-tier financial institutions to raise USD via the swap market. To cope with this, a large adjustment of $F-S$ quotes is required to attract offsetting arbitrage flow from highly rated banks. The price impact of 0.7 bp in Table 3, column (3) and (4), confirms this intuition. By the same token, a positive order flow (into USD at spot leg) observed in a situation when also deviations for banks with lower ratings occur (A-2/P-2 in Table 3) serves as a signal of even worse funding conditions. This requires an even greater adjustment in $F-S$ quotes by the dealer to restore FX swap market equilibrium, as indicated by the 1.1 bp price impact coefficient in column (1).

Our regressions indicate that swap order flow emerges as a more powerful explanatory variable to explain CIP arbitrage profits than the alternative variables we consider as controls in our regressions. Estimated coefficients on the dollar index are positive, but small and only barely statistically significant. Figure 7 summarizes the impact of swap market order flow, for different tenors, in periods of arbitrage. In all three cases (1-week, 1-month and 3-month), the price impact of order flow is positive and significant. The impact of order flow is higher for CIP profits by mid-tier banks, and it is higher for shorter maturities.

[Insert Figure 7 about here]

CIP arbitrage and central bank deposits. We now provide some evidence on the footprint of global banks' CIP arbitrage involving central bank deposit facilities. Our previous results showed that the JPY stands out as the currency with the most attractive CIP arbitrage opportunities, in particular when relying on the central bank deposit facility in the investment leg (Table 2). One would therefore expect that the pricing in FX swaps and the CIP arbitrage profits available by investing at the Bank of Japan's deposit facility has indeed attracted arbitrage capital.

Figure 8 shows JPY cash holdings by foreign banks operating in Japan (green bars), as well as the amounts placed in the deposit facility of the central bank (red bars). Panel (a) shows JPY holdings by highly rated banks, while those of all other global banks active in Japan are depicted in Panel (b). Blue bars represent the amount of net headquarter funding from abroad.

[Insert Figure 8 about here]

As can be gleaned from the graph, highly rated banks have bolstered their JPY cash holdings with the Bank of Japan substantially since the introduction of the QQE (Quantitative and Qualitative Easing) program in April 2013, primarily by channeling funds from their head office. This effectively exploits CIP arbitrage opportunities. In Panel (a) we superimpose the annual average CIP deviation that supports this interpretation. However, similar patterns cannot be observed for the set of globally active banks that do not enjoy a top rating, as is evident in Panel (b). This evidence is consistent with the prediction of the framework above that banks with access to cheap funding in USD exploit the arbitrage trade.

Limits to arbitrage scalability: evidence from USD CD issuances. Our previous results suggest that in order to arbitrage CIP deviations, the burden falls on a relatively small set of highly rated banks to supply a significant amount of USD in the FX swap market. What is preventing these high-rated banks from deploying even more capital for arbitrage purposes? To study this question we turn to an analysis of certificate of deposit (CD) issuance in USD markets. Descriptive statistics on issuance volumes are presented in Table 4.

[Insert Table 4 about here]

Drawing on the CD transactions of individual banks' with access to this funding market, Figure 9 depicts the corresponding profits from CIP arbitrage trades. A key takeaway is the large heterogeneity in funding costs across banks: Even within the set of highly rated banks that do have access to USD CD markets, there are quite a few that do not enjoy economically attractive arbitrage opportunities given their elevated funding costs in USD markets.[36]

[Insert Figure 9 about here]

[36] Also note that CIP arbitrage profits appear slightly lower when we consider volume-weighted averages of CD rates compared with baseline results using CP rates that do not take volume information into account (see Figure OA.6 in Online Appendix).

To shed light on the scalability of CIP arbitrage, we study the relationship between USD funding spreads (CD minus the OIS rate) and volume based on individual transactions in certificates of deposit. Our goal is to test whether the price of USD funding picks up as banks seek higher issuance volumes.

To test this, we rely on panel regressions of the form

$$r^{CD}_{i,t,m} - r^{OIS}_{t,m} = \beta_1 \cdot CDvolume_{i,t,m} + \lambda_{i,t} + \alpha_{t,m} + \varepsilon_{i,t,m} \tag{9}$$

where $r^{CD}_{i,t,m} - r^{OIS}_{t,m}$ is the CD-OIS spread for bank i at time t with maturity m, $CDvolum_{i,t,m}$ is the issued volume, $\lambda_{i,t}$ is bank-time fixed effects and $\alpha_{t,m}$ is maturity-time fixed effects. The standard errors are clustered at the bank level.

[Insert Table 5 about here]

By including bank-day fixed effects and maturity-day fixed effects, we can control for economically important unobservable effects. Important unobserved time-varying bank characteristics that may affect the banks' funding costs can, for instance, be the perceived risk on different banks' balance sheets. It also deals with the issue that longer term maturity funding spreads tend to increase more when funding liquidity conditions tighten. Finally, we report the result for each of the maturities separately to ensure that maturity effects are not driving our results.

Table 5 reports the results. We find that a USD 100 million increase in CD issuance volume corresponds to a 1 basis point increase in funding costs. Table 4 shows that USD 100 million is below the average amount of a CD primary market issuance. This Table also shows that the largest issuances have exceeded USD 4 billion. In our empirical analysis, we exclude issuances below USD 1 million to make sure that very small issuances, in particular those issued by small U.S. banks, do not contaminate our results. This means that for a given bank, at a given date and for a given maturity, controlling for time-varying bank and maturity characteristics, funding costs increase significantly by volume issued. This in turn suggests limited scalability of the arbitrage trades. Turning to the maturity-specific estimates, our results indicate that the volume effect is largest at the 3-month maturity. A USD 100 million increase in CD issuance volume corresponds to a 2.68 basis point increase in funding costs. Results are quantitatively similar when the sample is restricted to high-rated banks only.

What are the economic reasons why the USD supply curve is likely to be upward-sloping? One major reason is that the marginal investors in unsecured short-term bank liabilities, i.e. U.S. money market funds, care about concentration risk and do not consider banks with different risk profiles to be perfect substitutes for each other. For instance, if a high-rated bank increases issuance of short-term debt, typical investors may not be able to meet this demand due to limits on the concentration risk posed by large investments in specific issuers, even when the bank is of high quality. This may also increase the funding costs for other issuers when default probabilities across issuers are very similar. In this case, meeting the concentration limits for one issuer may transmit to other issuers with similar characteristics.

5. Quarter-end effects and CIP arbitrage

In this section, we take a closer look at spikes in short-term (e.g. 1-week and 1-month) LOOP violations around quarter-ends through the lens of our framework. Such spikes, documented in the recent work of Du, Tepper, and Verdelhan (2018), provide compelling evidence of banks' window dressing around key regulatory reporting dates (also see Krohn and Sushko (2017) and Abbassi and Bräuning (2018)). Seasonal dislocations in short-term interbank rates around reporting days for banks' regulatory capital requirements are not new (see e.g. Furfine, 1999). What is new, though, is that in recent years, quarter-end frictions have also spilled over to the FX swap market, magnifying dislocations in the law of one price during these short-lived episodes.

In line with our main thesis as laid out in the previous section, we argue that the abundance of liquidity in QE currencies has been a major factor contributing to the spikes in LOOP deviations, coupled with the incentives created by regulatory reporting.[37] It is important to note that for regulatory reporting purposes, an FX swap is treated as an *off-balance sheet* item (as opposed to repos, for instance, which increase the size of the balance sheet, see Borio, McCauley, and McGuire (2017)). This means that a globally active bank holding (excess) EUR liquidity on its balance sheet, can

[37] Especially uneven application of the leverage ratio across jurisdictions is an important factor for banks' window dressing for regulatory reporting purposes. When implementing the leverage ratio, jurisdictions have opted for different measurement approaches, in particular daily averages vs period-end snapshots.

lend it out via an FX swap in exchange for USD. The result is that the cash held in EUR is replaced with USD cash on the balance sheet. If the bank simultaneously lets its USD borrowing mature and uses the USD cash obtained via the swap to pay down the debt, the consolidated balance sheet of the bank will be reduced (Figure OA.7(a) in the Online Appendix illustrates the balance sheet effects). What this boils down to is that due to such incentives, excess liquidity in EUR, JPY, and CHF is just waiting to be deployed in the FX swap market around major reporting dates, with the aim of reducing banks' balance sheets.

To illustrate this phenomenon, Figure 10 shows fluctuations in 1-week LOOP violations based on LIBOR (as in Du, Tepper, and Verdelhan, 2018). Vertical lines indicate key dates associated with a significant rise in central banks' balance sheets (the ECB's public sector asset purchase program, the Bank of Japan's quantitative and qualitative easing, and in the case of the Swiss National Bank, the introduction of the EUR/CHF floor regime). The spikes, all aligned with quarter-end periods, only emerge in the period after the substantial rise in created central bank reserve balances.[38] Table OA.X in the Online Appendix presents a regression analysis showing that end-of-quarter effects were not present prior to the introduction of QE by major foreign central banks.

[Insert Figure 10 about here]

When the amount of liquid assets in the form of reserves is abundant, a reduction in liquid reserves via FX swaps is advantageous over reporting days due to potential bank levies and other regulatory fees that are calculated based on the *size* of the balance sheet.[39] For instance, a 10 basis point fee translates into a maximum implied 1-week rate of around 5 per cent.[40] This means that banks with excess EUR liquidity and 1-week USD borrowing that matures in the week before the reporting day are willing to pay 5 percentage points more in an FX swap transaction compared to the direct USD rate.[41]

[38] In the case of the CHF, a few spikes occur prior to implementation of the exchange rate peg with the euro. A likely reason is the Swiss National Bank's efforts to fight the appreciation of the currency via (unsterilized) FX interventions and provision of central bank reserves through collateralized loans, which significantly expanded the CHF reserve balances held by commercial banks.

[39] Examples of regulatory costs over reporting days include G-SIB surcharges, leverage Ratio, resolution fees and deposit guarantee fees.

[40] This is approximately given by X in $\frac{X}{52weeks} = 10bp$.

[41] Remember that as banks sell securities to the central bank conducting asset purchases, banks' balance sheets increases due to reserve balances they receive in return, but without generating a compensation in the form of a higher return. This is especially pronounced in the case of negative interest rates as positive interest rate margins are difficult to preserve.

As in our framework above, such imbalances induce a price reaction from FX swap dealers in order to create sufficient incentives for other counterparties to supply USD in the FX swap market. The main problem over reporting days is that non-U.S. banks domiciled in QE currencies will obviously not supply USD due to the reasons outlined above. This means that a large share of potential arbitrageurs stays away from the market, or in fact contributes to additional USD demand in the FX swap market. Consequently, a significantly smaller group of banks than in normal circumstances must supply the necessary USD in the swap market. First, such a massive redistribution of short-term USD funding is difficult in a short period of time. Second (as mentioned above), money market investors face quantity constraints caused by concentration risk limits, as discussed in the previous section. An indication that such concentration risk limits bind is MMF's increased use of the Federal Reserve's reverse repo facility over reporting days. All this means that FX swap dealers have a strong incentive to adjust the price sufficiently in order to limit the USD demand pressure from banks with large amounts of central bank reserves on their balance sheets in other currencies.

Some of this arbitrage flow (supplying USD at a premium in the FX swap markets against EUR, CHF or JPY) will then be invested at the deposit rate offered by the foreign central bank. For banks that do not have access to the central bank deposit facility, risk-free investment alternatives may be short-term reverse repos and T-bills that mature right after year-end/quarter-end. Importantly, however, the pricing of these investment vehicles (unlike the rate of remuneration on central bank deposits) responds to volume, thereby reducing possible arbitrage profits. Given that collecting data on all bonds that mature right after reporting days is difficult, Figure 11 shows an example for the price response of a German Treasury bill that, given its maturity profile, would be suitable as an investment vehicle around such an episode. The Figure shows that the T-bill yield drops significantly, in turn making the arbitrage significantly less attractive. In Panel (b) we show that EUR GC repo rates also have significant drops around quarter-end and year-end.

[Insert Figure 11 about here]

However, the costs involved with carrying balance sheet over the end-of-quarter indeed generate fairly extreme outcomes in the FX swap market. In Table 6, we interact the price impact of swap order flow with an End-of-Quarter dummy, and study 1-month and 1-week maturity (end-of-quarter effects do not come into play for 3-month maturity). Results are largely as before, but are about twice as large during the End-of-Quarter period (1 week (month) before for 1-week (-month) maturity). These large price impacts reflect the strong incentives for banks to swap liquidity-abundant currencies into USD.

[Insert Table 6 about here]

To sum up, excess liquidity in major currency areas other than USD, coupled with bank capital regulations tied to balance sheet size on the reporting day, create large FX swap flows into USD around quarter-ends aimed at bringing down the size of the consolidated balance sheet. FX swap market makers must grant CIP deviations in order to elicit opposite flows. This will be picked up by those banks with good access to USD and a flexible balance sheet. The group of arbitrageurs is very small, however, as even high-quality banks domiciled in QE currencies have incentives to borrow USD through the FX swap market. Importantly, the LOOP violations only emerged in FX swap markets following the significant balance sheet expansion of central banks in non-USD currencies. The reason is that compared to a normal situation, banks now have much more liquid balances to draw on in order to reduce the balance sheet size using FX swaps.

6. Conclusion

The absence of arbitrage is the most fundamental mechanism in financial markets. Common measures suggest that CIP, a no-arbitrage condition once considered to be a cornerstone of international financial markets, is broken. We argue that to understand the CIP conundrum, a new perspective is warranted. In the post-crisis environment, characterised by fragmented USD funding markets and a substantial heterogeneity in funding costs (both across banks and across currency areas), it is no longer possible for the law of one price to hold for the full spectrum of interest rates simultaneously. Careful attention needs to be paid to select the appropriate interest rates and to account for the key costs and risks faced by the potential arbitrageur. Unpacking the true marginal funding costs faced by banks has become especially difficult.

The main message from our paper is that the law of one price in fact holds remarkably well for the majority of market participants when considering money market rates that reflect banks' marginal funding costs. Commonly used measures such as the cross-currency basis based on OIS rates represent differences in funding liquidity premia across currencies, but not the existence of a "free lunch".

That said, we find that economically attractive CIP arbitrage opportunities do exist — but, they are confined to a few highly rated global banks. The key reason why CIP arbitrage for these banks is profitable is favourable access to USD Commercial Paper (CP) and Certificates of Deposit (CD) markets where banks can raise funding from non-bank institutional investors at the lowest cost. Moreover, the fact that these banks operate globally gives them access to safe investment vehicles in foreign currency, particularly central bank deposit facilities.

This raises the fundamental question of how a situation with riskless arbitrage profits for a confined set of high-rated banks can persist over a prolonged period of time. We show conceptually how such arbitrage opportunities emerge as an equilibrium outcome as FX swap dealers set prices to avoid inventory imbalances. Low-rated banks find it attractive to turn to the FX swap market to cover their USD funding, while swap dealers elicit opposite (arbitrage) flows by high-rated banks. The price impact of FX swap order flow is particularly strong — and arbitrage profits greatest for high-rated banks — when lower-tier banks have an incentive to turn to the FX swap market to obtain USD funding.

Such arbitrage opportunities for a few high-rated banks can persist as the arbitrage positions are difficult to scale. Drawing on issuance data for USD CDs, we show that funding rates adjust as soon as arbitrageurs increase their positions, in turn significantly reducing profits. All in all, the evidence presented in this paper suggests that the main paradigm of CIP — i.e. the non-existence of riskless arbitrage profits after accounting for the risk and relevant costs incurred by the arbitrageur — still remains largely valid in post-crisis financial markets, at least for the majority of market participants.

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Appendix A: Data sources

[Insert Table A.1 about here]

Appendix B: Transaction costs

This section lays out how we account for bid-ask spreads when computing CIP arbitrage profits. To study CIP arbitrage at a precision level akin to that of market participants, we take all market conventions into account. Rewriting Equations (2)-(3) in the main text using FX swaps, represented by $\overline{F^b - S^a}$ (here at bid), instead of (outright) forwards, CIP deviations can be expressed as:

$$Dev^b_{CIP} = -r^a_{\$} + \left[\frac{S^a + \overline{F^b - S^a}/10^4}{S^a} \left(100 + r^b_{\star} \frac{D}{360}\right) - 100 \right] \frac{360}{D}, \tag{B.1}$$

$$Dev^a_{CIP} = -r^a_{\star} - \left[\frac{S^b}{S^b + \overline{F^a - S^b}/10^4} \left(100 + r^b_{\$} \frac{D}{360}\right) - 100 \right] \frac{360}{D}. \tag{B.2}$$

where D represents days to maturity and 10^4 is a factor scaling the swap since it is quoted in "swap points" (units of the last decimal in the difference between the spot and the forward).[42]

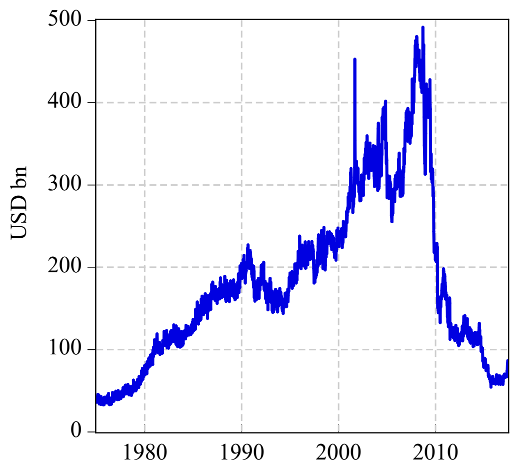
The above equations define CIP deviations as the cross-currency basis and simply state that the deviation is positive (CIP arbitrage is profitable) if the percentage cost of borrowing is lower than the percentage gain from lending in foreign currency and covering the FX risk with a swap contract. In Equation (B.1), borrowing is at the ask rate in USD money markets ($r^a_{\$}$), and lending at the bid rate ($r^b_{\star}$) in the foreign money market. For more details confer the Online Appendix A.

[42]Days to maturity are obtained from Bloomberg and respect all market conventions and non-trading days in both currencies involved (for further details, see Akram, Rime, and Sarno, 2008). The scaling factor is 10^2 for JPY. Days in a year may also differ, being 365 for GBP and 360 for the other currencies.

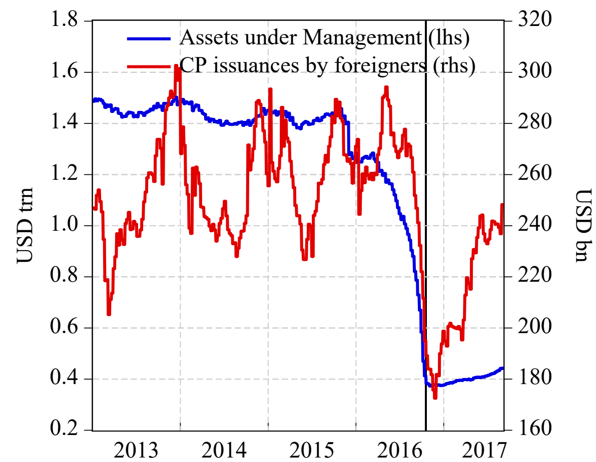
Tables and Figures

Figure 1
Activity in USD money markets

(a) Activity in U.S. interbank markets



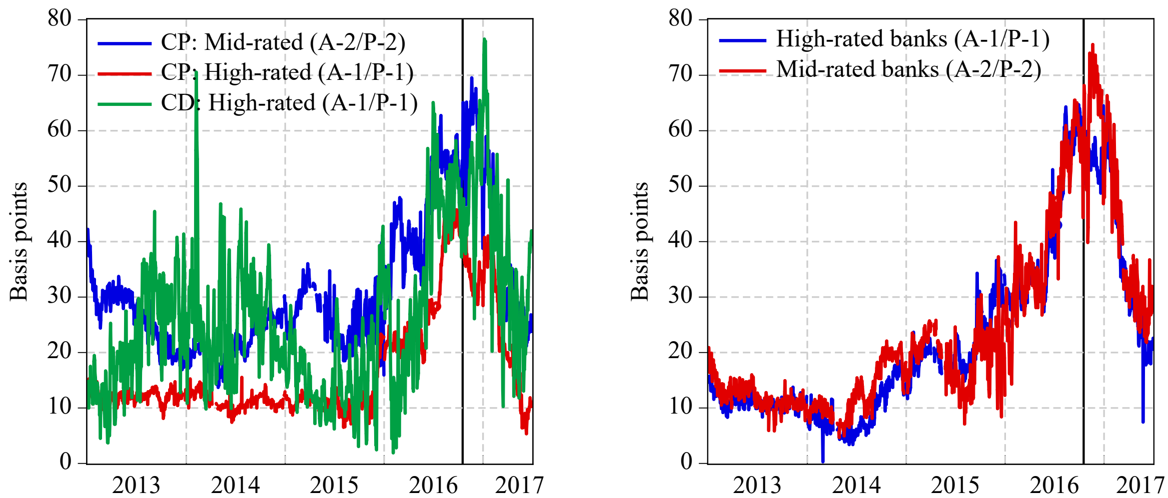
(b) U.S. prime money market funds



Notes: The Figure shows the activity in U.S. money markets. Panel (a) shows the evolution of weekly aggregate volumes in U.S. interbank markets. The sample period is from January 1975 until June 2017 and represents interbank loans issued by all commercial banks. The original source is the H.8 Assets and Liabilities of Commercial Banks in the United States released by the Board of Governors of the Federal Reserve System. The left-hand axis of Panel (b) shows the evolution of the assets under management of prime U.S. money market funds in USD billion. The right-hand axis shows the volumes issued by foreign financial institutions in the U.S. commercial paper market (in USD billion). The vertical line marks the introduction of the Money Market Reform on October 14, 2016, and the sample is January 2013 — June 2017. Source: St. Louis FRED database.

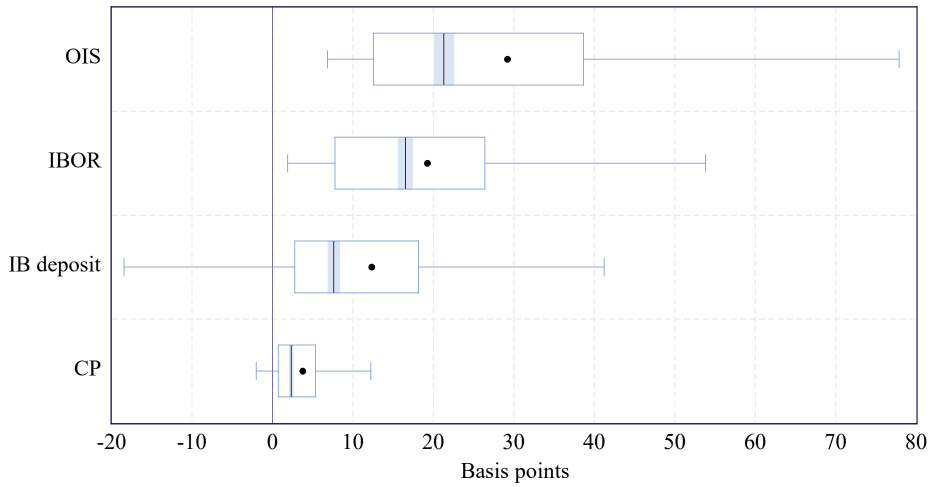
Figure 2
USD wholesale funding market spreads (3-month maturity)

(a) CP-OIS and CD-OIS spreads **(b) USD CP-OIS minus average foreign CP-OIS spread**



Notes: The Figure depicts the evolution of 3-month wholesale funding market spreads in USD compared to major foreign currencies in the post-GFC period (in basis points). Panel (a) shows spreads of USD Commercial Paper (CP) over OIS rates for high-rated (A-1/P-1 rating) and mid-rated (A-2/P-2) banks, together with moving average (10 days) of volume-weighted Certificate of Deposit (CD) rates, over OIS, from issuances by high-rated banks. Panel (b) depicts the difference between USD CP-OIS spreads and that of EUR, GBP and JPY (averaged across the three currencies) for high-rated (A-1/P-1) and mid-rated (A-2/P-2) banks. The vertical line indicates October 14, 2016, the date of the implementation of the US Money Market Fund reform. Sample: January 2013 — June 2017.

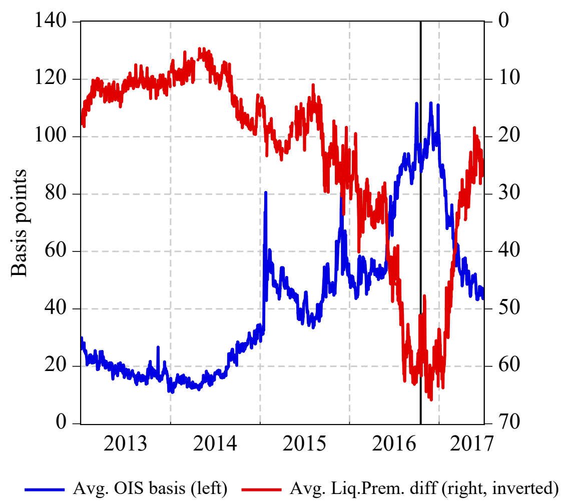
Figure 3
LOOP deviations for different money market rates (3-month maturity)



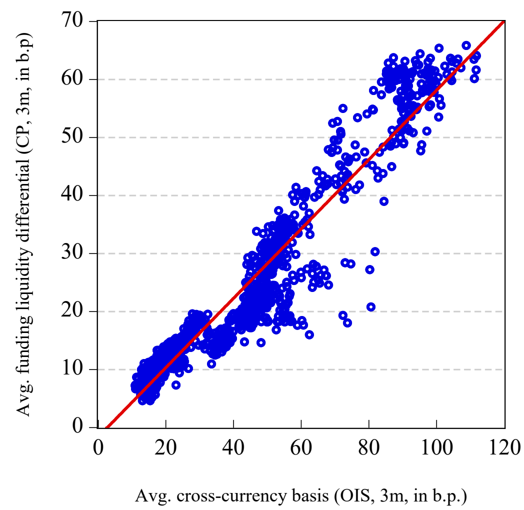
Notes: The Figure shows box plots displaying LOOP deviations, measured in basis points, for different 3-month money market rates. The depicted LOOP deviations compare the direct foreign currency borrowing rate and the implied rate by swapping from USD. Positive numbers suggest that the swap-implied rate from USD is cheaper. For ease of exposition, the average across the currencies for which we have CP-rates (EUR, JPY and GBP) is shown and LOOP deviations for CP rates are averaged across rating categories. Elements of the box plot are as follows: the box itself represents the first and third quartile; inside the box, the mean is represented by a dot, while the median by a line; the shaded area around the median represents the 95% confidence interval; the staples (end of straight line) represent the value of the last data point within 1.5 from either the first or the third quartile. Sample: January 2013 – June 2017.

Figure 4
Funding liquidity premia and the cross-currency basis (3-month maturity)

(a) Cross-currency OIS basis and funding liquidity premium differentials



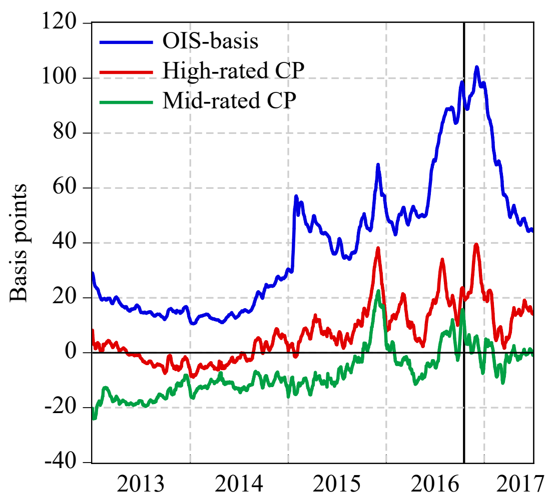
(b) Cross-currency OIS basis vs. funding liquidity premia (b.p)



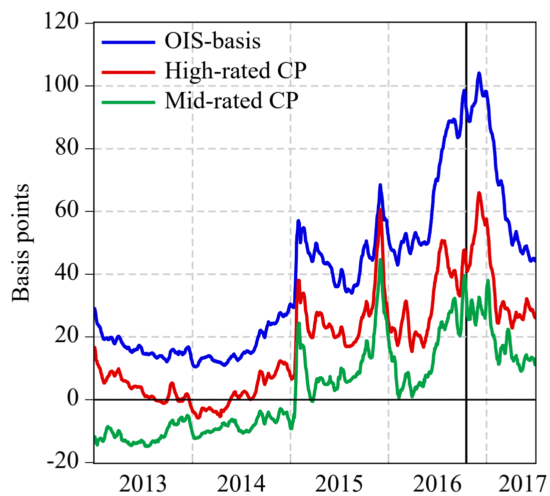
Notes: The Figure illustrates the relationship between funding liquidity premia and the cross-currency basis. The cross-currency basis is calculated from OIS rates. Panel (a) compares the time series of the 3-month OIS-basis (left-hand axis) with the average funding liquidity differential based on CP-rates (right-hand axis, inverted scale). The vertical line in Panel (a) indicates October 14, 2016, the date of the implementation of the US Money Market Fund reform. Panel (b) shows a scatter-plot for the average 3-month cross-currency basis based on OIS rates (horizontal axis) together with average funding liquidity premium differentials vis-à-vis USD (vertical axis) based on CP rates. Averages are across EUR, CHF and JPY. Sample: January 2013 – June 2017.

Figure 5
Risk-free 3-month CIP arbitrage opportunities for global banks compared to OIS basis. Average over EUR, CHF and JPY.

(a) Invest in T-bills

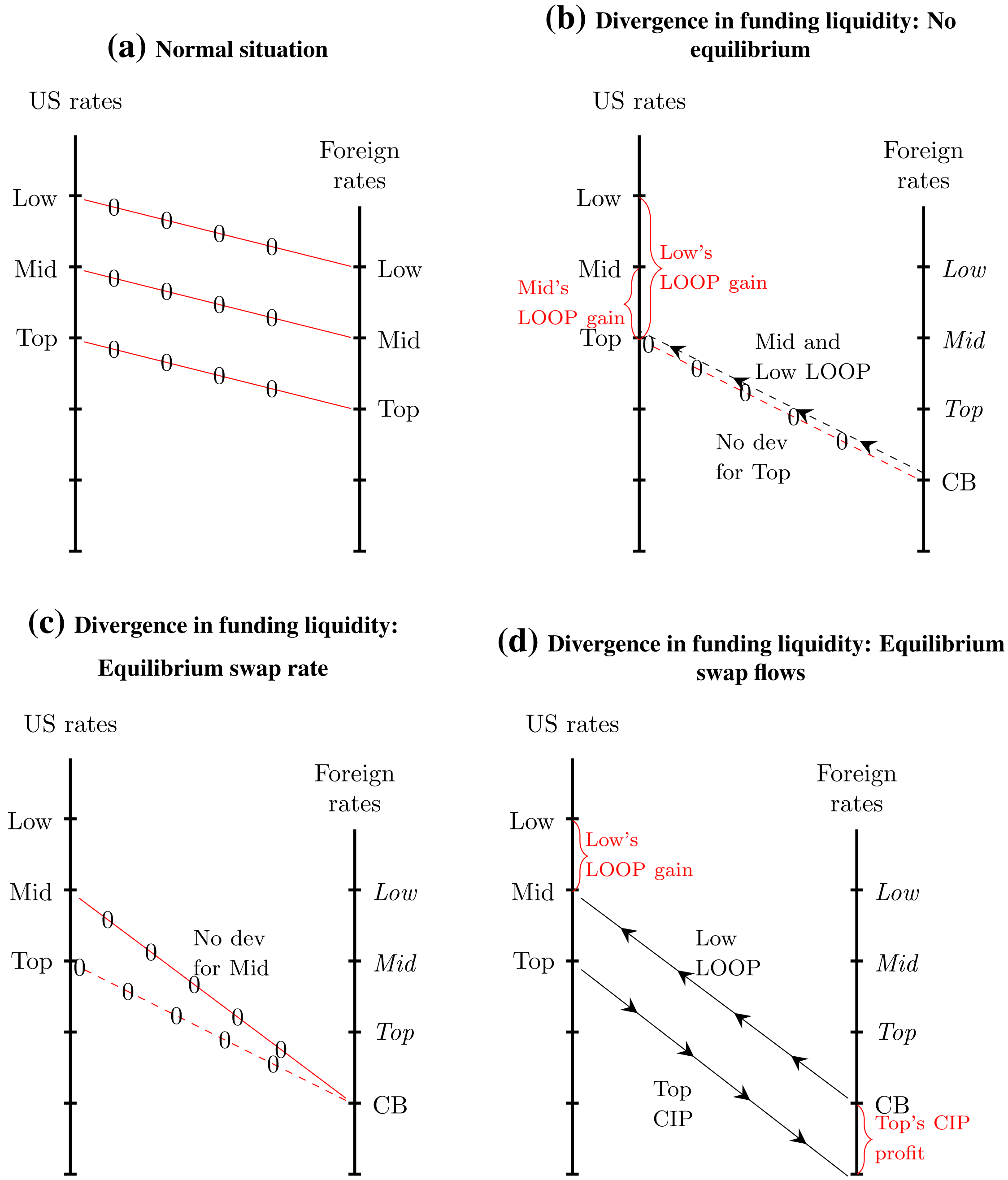


(b) Invest in CB deposits



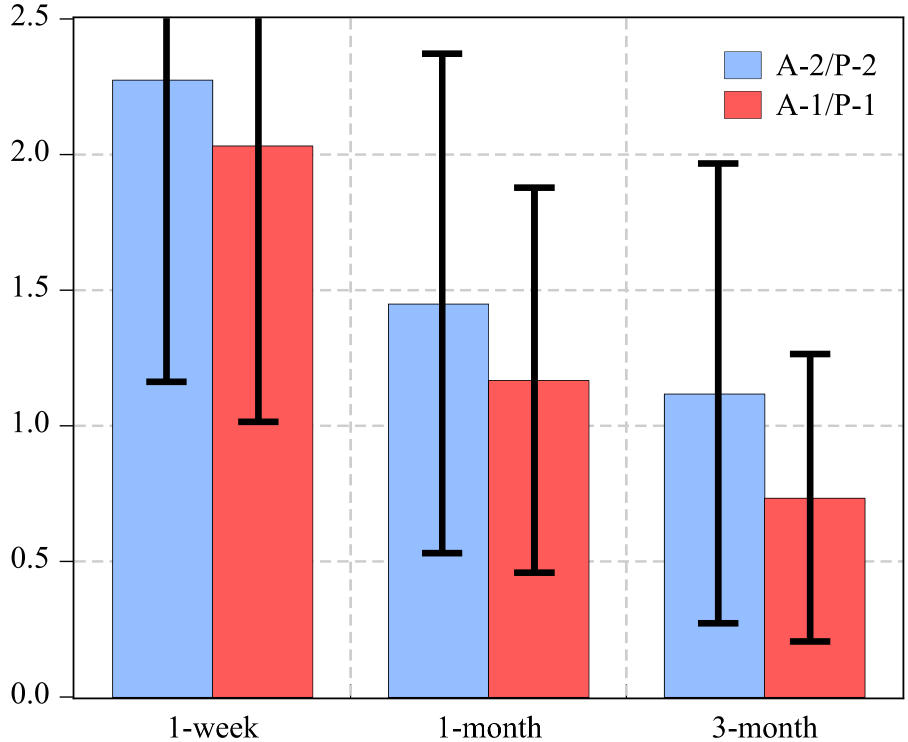
Notes: The Figure shows risk-free CIP arbitrage profits for global banks when funded via the issuance of USD commercial paper, swapping into foreign currency and placing the funds in foreign Treasury bills (panel a) or the foreign central banks' deposit facility (panel b). Funding rates differ for mid-rated banks (A-2/P-2) and high-rated banks (A-1/P-1). In both panels we also show the 3-month OIS basis. All series are smoothed with a 2-week moving average. The vertical lines indicate October 14, 2016, the date of the implementation of the US Money Market Fund reform. Sample: January 2013 – June 2017.

Figure 6
FX swap market equilibrium



Notes: The Figure characterizes FX swap market equilibrium, by illustrating the link between various types of interest rate differentials, swap rates and the direction of swap flows. The two vertical lines indicate the interest rate levels in the two countries, exemplified by the "U.S." (left) and "Foreign" (right). The curve connecting the two interest rates is the FX swap-implied interest rate differential (in short, the "swap rate"). Since all market participants face the same swap rate, these swap rate curves are shifted vertically. A red line marked with zeros means that there are no LOOP deviations (Panel a). The solid lines represent market rates, whereas the dashed line represents a hypothetical rate. The black line suggest a profitable opportunity, and the arrows show the direction of swap flows in the "spot leg" of the swap (Panels b-c). Arrows from US rates mean a profitable opportunity by directly raising dollars in U.S. funding markets. In Panel (d), the arrows from U.S. indicate a CIP deviation because the risk-free investment rate is higher than the implied borrowing rate. The arrow to the U.S., however, indicates a LOOP deviation as there are no risk-free U.S. investment opportunities available at higher rates than the swap-implied rate.

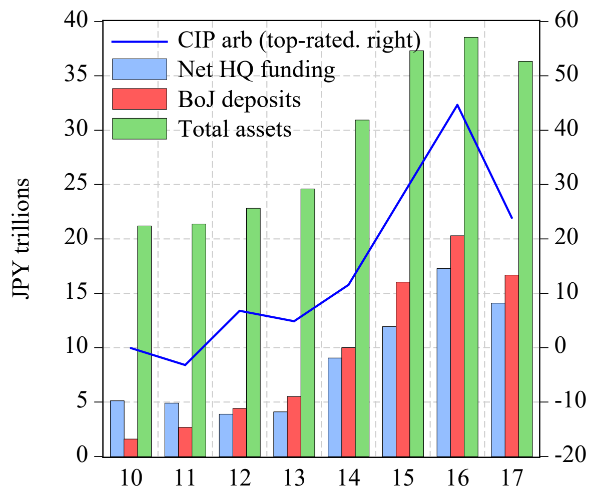
Figure 7
Relation between swap order flow and CIP arbitrage profits across maturities



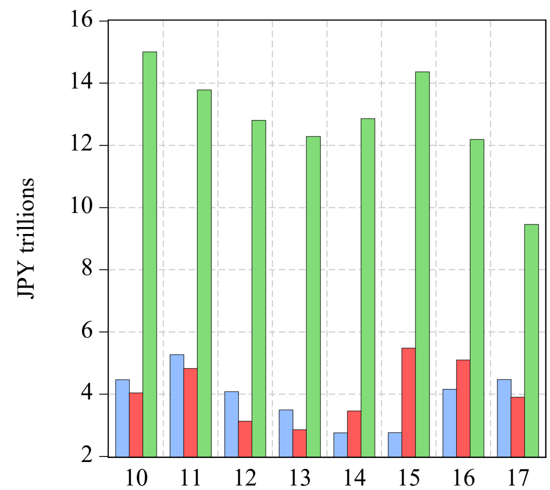
Notes: The Figure shows the impact coefficient of (standardized) swap order flow on CIP arbitrage profits (funding in US CP-rates and investing in CB deposits), conditioned on being in a positive arbitrage state, for three different maturities. Vertical lines indicate $\pm$ 2 $\times$ coefficient standard errors, which are symmetric but truncated at the top if they reach outside the graph area. Regression results are based on regressions similar to column (1) and (3) in Table 3. Coefficients measure the impact of a one standard deviation change in swap order flow. See Figure OA.5 in the Online Appendix for other regression specifications. Sample for estimation: January 2013 – June 2017.

Figure 8
Foreign banks' cash deposits with Bank of Japan

(a) High-rated banks (A-1/P-1)



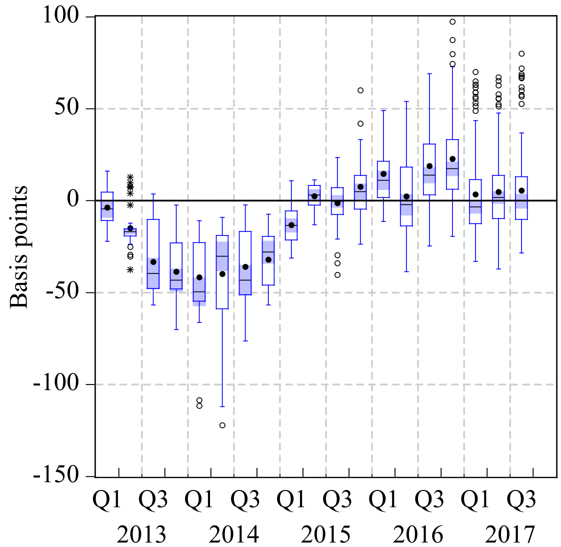
(b) Mid-rated banks (A-2/P-2)



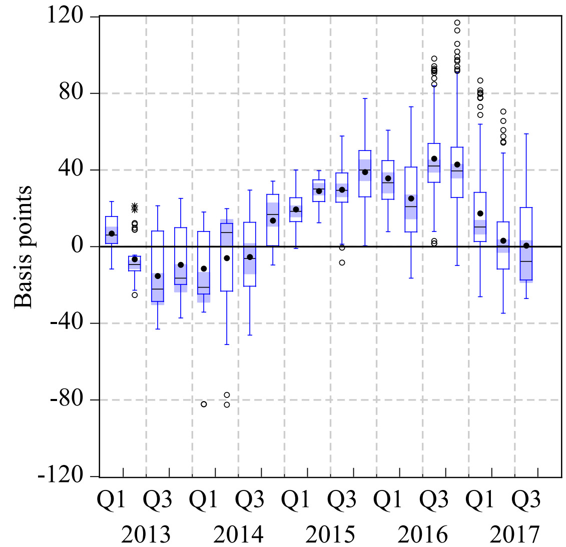
Notes: The Figure shows the assets, measured in trillions of JPY, of global banks' subsidiaries in Japan, for different rating categories. Green bars show total assets, red bars are holdings of cash (held at the Bank of Japan deposit facility), and blue bars show net funding by headquarters. High-rated banks (Panel a) are rated A-1/P-1 (and include some A-1+/P-1), while Panel (b) is for all other banks. In Panel (a) we superimpose the average CIP arbitrage profit recorded in June each year in basis points (on right axis) from funding in CP rates and deposting the funds in the Bank of Japan's deposit facility. Source: KPMG Japan.

Figure 9
Dispersion in CIP arbitrage opportunities (funded via CD issuance) across high-rated banks

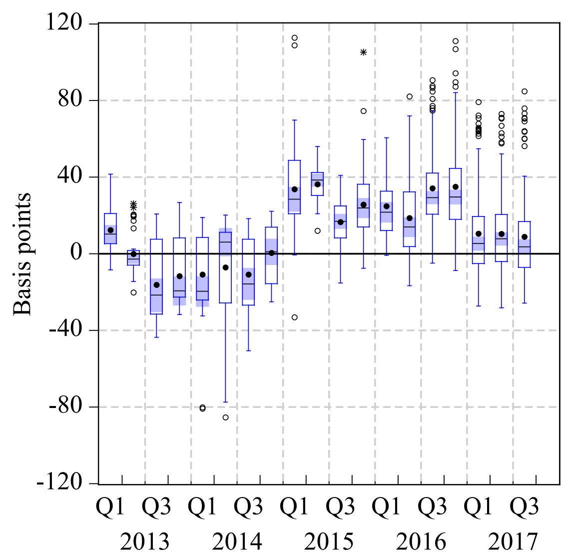
(a) EUR



(b) JPY



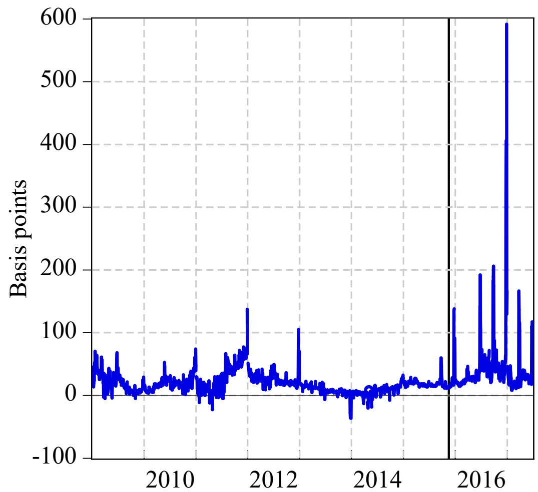
(c) CHF



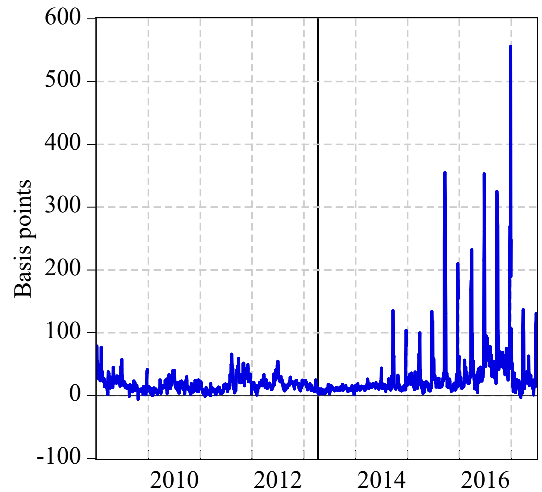
Notes: The Figure shows the dispersion in CIP arbitrage opportunities, when invested in central bank deposits, across high-rated (A-1/P-1) banks given their heterogeneity in funding costs in USD CD markets. Positive numbers indicate positive arbitrage profits. The dispersion is captured by quarterly box plots. The box shows the first and third quartile of the data, together with the mean (dot) and median (line). The vertical lines measure the distance to points within a range (1.5) outside the inter quartile range, while the dots outside are defined as outliers. Panels (a-c) show CIP arbitrage opportunities when swapping to EUR, JPY and CHF, respectively.

Figure 10
LOOP violations, End-of-Quarter effects and implementation of Quantitative Easing (1-week maturity)

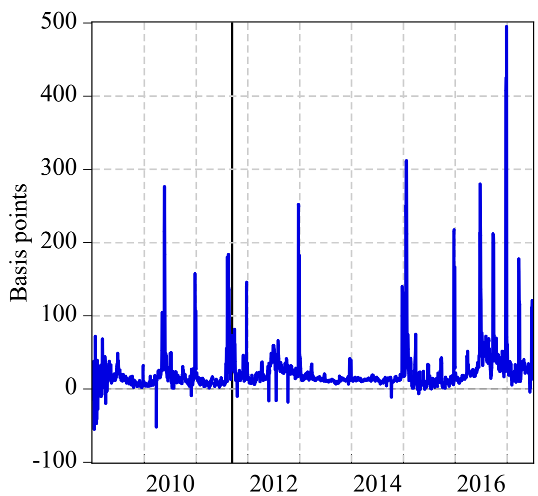
(a) EUR



(b) JPY



(c) CHF

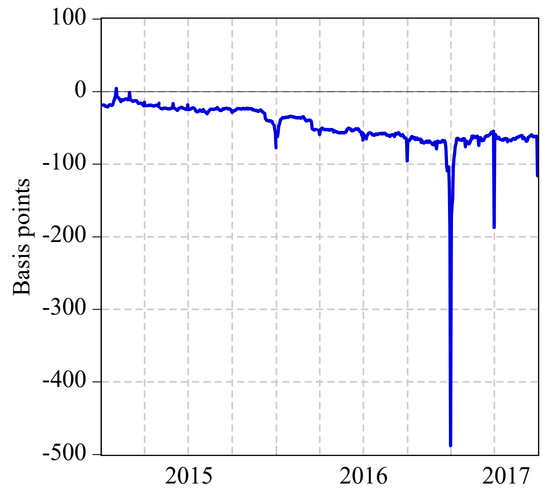


Notes: The Figure shows fluctuations in 1-week LOOP deviations (based on LIBOR rates). Positive values indicate that the synthetic LIBOR rate (FX swapped from EUR, JPY and CHF) is higher than the direct LIBOR rate in the U.S. The vertical lines indicate key dates associated with large-scale central bank balance sheet expansion that led to a substantial rise in reserve balances in the three currency areas (introduction of QQE in Japan, PSPP in the euro area and the introduction of the CHF/EUR floor system). Sample: Jan 2009 — July 2017.

Figure 11
Two examples of German investment rates End-of-Quarter

(a) Treasury

(b) Repo



Notes: Panel (a) shows the interest rate on a German Treasury bill (BUBILL 0 01/10/18) maturing on January 10, 2018. Panel (b) shows the euro General Collateral (GC) repo rate for collateral issued only by the German government. The index is calculated from trades executed on either the BrokerTec or the MTS electronic platform and all transactions are centrally cleared. The data is published by NEX Data.

Table 1
Comparison of money market spreads for different currencies (3-month maturity)

	Mean	Median	Std. Dev.	Obs.
	A: IBOR interbank rates			
AUD	20.97	20.90	8.21	1,171
CAD	31.94	28.08	6.46	1,130
CHF	-11.36	-12.62	10.74	1,137
EUR	9.31	10.00	4.19	1,150
GBP	11.16	10.24	3.80	1,136
JPY	4.97	5.40	2.71	1,137
USD	18.45	14.56	8.22	1,137
	B: Interbank deposit rates			
AUD	49.26	50.00	18.27	1,173
CAD	30.44	25.40	14.33	1,174
CHF	-1.78	2.85	16.19	1,174
EUR	12.73	12.90	5.43	1,172
GBP	28.05	28.00	11.47	1,173
JPY	3.34	6.20	10.98	1,174
USD	31.48	29.50	14.06	1,173
	C: Commercial paper			
	Mid-rated banks (A-2/P-2)			
EUR	10.71	13.10	7.63	1,105
GBP	18.76	18.80	5.03	1,099
JPY	-8.50	-7.12	15.32	1,054
USD	31.41	27.80	12.13	1,099
	High-rated banks (A-1/P-1)			
EUR	-0.22	0.10	5.68	1,104
GBP	8.51	8.01	3.84	1,101
JPY	-25.73	-26.96	21.83	1,098
USD	17.00	12.37	9.39	1,099

Notes: The Table presents descriptive statistics for spreads between different 3-month money market rates and OIS rates across currencies. Panel A presents for IBOR rates, panel B for interbank deposits, while Panel C presents results for Commercial Paper (CP) for high-rated (A-1/P-1) and mid-rated (A-2/P-2) banks. All rates are measured as ask rates, and mean, median and standard deviation of spreads are expressed in basis points. Sample: January 2013 – June, 2017. See the Online Appendix Table OA.I for 1-week and 1-month tenors.

Table 2
Risk-free CIP arbitrage funded via the CP market (3-month maturity)

	Investment rate: Central bank deposit facilities					Investment rate: Treasury bills				
			Deviation					Deviation		
	Median	Std.	(%D)	(%M)	Obs.	Median	Std.	(%D)	(%M)	Obs.
	I: Post-crisis to beginning MMF reform period (Jan 2013 – Mar 2016)									
	A. Mid-rated banks (A-2/P-2)									
AUD	**-54.8**	11.5	0	0	701	**-47.7**	81.8	0	0	222
CAD	**-20.2**	7.0	0	0	783	**-29.5**	7.0	0	0	758
CHF	**1.4**	16.4	56	33	783	**-12.8**	11.2	14	4	762
EUR	**-22.0**	11.9	7	1	780	**-15.7**	6.6	5	0	723
GBP	**-14.1**	5.4	1	0	782	**-32.0**	7.7	0	0	745
JPY	**4.6**	14.8	68	55	781	**-4.9**	11.4	32	13	537
	B. High-rated banks (A-1/P-1)									
AUD	**-43.8**	11.4	0	0	701	**-34.5**	80.8	0	0	222
CAD	**-7.7**	5.4	14	2	783	**-16.1**	5.3	1	0	758
CHF	**14.2**	17.4	100	97	783	**0.6**	11.4	53	15	762
EUR	**-6.8**	13.5	34	26	780	**-1.4**	7.5	42	19	723
GBP	**-0.3**	3.6	47	25	782	**-18.7**	7.4	2	0	745
JPY	**14.2**	14.7	100	100	781	**6.0**	11.7	90	77	537

Notes: The Table shows CIP deviations, measured in basis points, for an implementable strategy involving borrowing in the U.S. money market. The sample covers the post-crisis period and prior to the adjustment phase of the U.S. money market fund (MMF) reform (January 2013–March 2016). Positive numbers represent arbitrage profits. The Commercial Paper (CP) funding rate differs according to two rating categories, either high-rated banks (A-1/P-1) or mid-rated banks (A-2/P-2). Two risk-free choices for the investment leg are considered: central bank deposit facilities (left-hand panel) and T-bills (right-hand panel). Columns give the median CIP arbitrage profit, the standard deviation of CIP arbitrage profits and the proportion of days (%D) and months (%M), as 20 consecutive days, during the sample when a positive arbitrage profit is observed.

Table 2
(Continued) Risk-free CIP arbitrage funded via the CP market (3-month maturity)

	Investment rate: Central bank deposit facilities					Investment rate: T-bills				
			Deviation					Deviation		
	Median	Std.	(%D)	(%M)	Obs.	Median	Std.	(%D)	(%M)	Obs.
	II. MMF reform sample (Apr 2016 – June 2017)									
	A. Mid-rated banks (A-2/P-2)									
AUD	**-67.6**	8.9	0	0	294	**-50.1**	9.2	0	0	111
CAD	**-29.5**	6.2	0	0	316	**-30.5**	7.9	0	0	316
CHF	**19.6**	10.5	99	84	316	**7.9**	8.6	85	44	310
EUR	**10.2**	9.4	83	75	316	**-11.9**	8.1	3	0	316
GBP	**-7.1**	7.2	13	0	315	**-24.5**	8.5	0	0	211
JPY	**26.4**	14.1	100	100	307	**8.4**	11.5	78	37	182
	B. High-rated banks (A-1/P-1)									
AUD	**-52.3**	5.9	0	0	294	**-33.6**	8.0	0	0	111
CAD	**-13.3**	6.5	4	0	316	**-13.8**	7.5	3	0	316
CHF	**34.8**	13.2	100	100	316	**23.4**	11.0	100	98	310
EUR	**25.5**	11.4	100	100	316	**4.4**	8.2	71	27	316
GBP	**8.8**	8.9	85	52	315	**-7.4**	8.0	17	0	211
JPY	**42.9**	16.3	100	100	307	**26.4**	14.4	97	88	182

Notes: The Table shows CIP arbitrage profits, measured in basis points, for an implementable strategy involving borrowing in the U.S. market. The sample covers the transition phase of the U.S. money market fund reform from April 2016 – Dec 2016. Positive numbers represent arbitrage profits. The Commercial Paper (CP) funding rate differs according to two rating categories, either high-rated banks (A-1/P-1) or mid-rated banks (A-2/P-2). Two risk-free choices for the investment leg are considered: central bank deposit facilities (left-hand panel) and T-bills (right-hand panel). Columns give the average CIP arbitrage profit, the standard deviation of CIP arbitrage profits and the proportion of days (%D) and months (%M), as 20 consecutive days, during the sample when a positive arbitrage profit is observed.

Table 3
CIP arbitrage and FX swap market order flow imbalances

	Mid-rated (A-2/P-2)		High-rated (A-1/P-1)	
	(1)	(2)	(3)	(4)
Lagged level	-0.035	-0.035	-0.020	-0.020
	(-3.23)	(-2.99)	(-2.12)	(-1.97)
Swap OF, in arb.	1.116	1.138	0.733	0.743
	(2.64)	(2.61)	(2.77)	(2.75)
Swap OF, no arb.	0.172	0.182	0.192	0.215
	(3.95)	(4.10)	(5.03)	(5.45)
Dollar index, in arb.		0.008		0.014
		(1.43)		(3.10)
Dollar index, no arb.		0.005		0.004
		(1.50)		(1.95)
Lagged dependent	-0.186	-0.203	-0.107	-0.127
	(-3.51)	(-4.16)	(-1.50)	(-2.01)
Obs.	5,969	5,569	5,969	5,569
adj.R^2	0.08	0.10	0.06	0.08

Notes: The Table shows results from panel regressions of changes in 3-month CIP deviations on FX swap order flow, across six different currencies. CIP deviations are based on an arbitrage strategy funded in the U.S. commercial paper market for either mid-rated (A-2/P-2) or high-rated (A-1/P-1) banks and measured in basis points. The constant (not reported) and error-correction term (lagged level of CIP deviation) have constant coefficients across deviation regimes, while the other explanatory variables are allowed to have different effects, depending on whether a CIP deviation exists or not. Swap order flow is standardized by its standard deviation, while the broad dollar index return is measured in basis points. Robust t-statistics (cross-sectional clustering) are reported in parenthesis below coefficient estimates. Sample: January 2013 – June 2017.

Table 4
Descriptive statistics on issuance volume of USD Certificates of Deposit (mio USD)

	Total	Mean	Std.Dev.	Max	Obs
Aggregate (average)	84,179	134	172	1,268	1,215
Small countries (average)	6,704	77	85	354	209
Canada	388,332	268	306	1,930	1,449
Japan	343,026	153	188	2,730	2,242
USA	291,785	20	67	1,400	14,887
China	250,944	40	59	600	6,353
Hong Kong	211,500	100	168	1,700	2,115
Switzerland	187,590	390	522	4,550	481
Sweden	155,805	255	277	1,600	611
France	91,875	175	199	3,200	525
Netherlands	77,724	306	355	1,960	254
United Kingdom	72,800	182	232	1,610	400
Germany	68,392	332	565	4,640	206
Australia	32,500	250	426	3,000	130

Notes: The Table presents summary statistics for issuance volume of Certificates of Deposit (CD) in USD. The first row presents aggregate numbers across all countries, while the 10 countries with the largest total issuances are presented in the following rows. Sample: January 2013 – June 2017.

Table 5
Impact of CD issuances on USD funding costs

	All banks				High-rated banks			
	Maturity							
	All	All	3-month	6-month	All	All	3-month	6-month
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Amount Issued	1.05	0.85	2.68	0.75	0.91	0.86	3.40	0.69
	(2.98)	(2.11)	(1.96)	(2.42)	(2.89)	(2.42)	(2.15)	(2.01)
Fixed effects:								
Bank × day	X		X	X	X		X	X
Maturity × day	X	X			X	X		
Bank × month		X				X		
Obs	8,283	15,449	2,623	3,203	3,581	8,015	1,190	1,340

Notes: The Table presents panel regressions for the impact of CD issuance volume on the CD-OIS spread. Maturities included are 1-month, 3-month and 6-month. All issuances considered are larger than USD 1mio. Coefficients measure impact in basis points for a 100 mio USD issue. t-values, based on standard errors clustered at the bank level, in parenthesis, singleton observations removed iteratively. Sample: January 2013 – June 2017.

Table 6
CIP arbitrage, FX swap order flow market imbalances, and End-of-Quarter effects

			1-month		1-week	
			A-2/P-2	A-1/P-1	A-2/P-2	A-1/P-1
			(1)	(2)	(3)	(4)
Lagged level			-0.046	-0.028	-0.198	-0.146
			(-2.58)	(-2.28)	(-3.73)	(-2.26)
Swap OF						
	In arb	EoQ	1.771	1.998	7.839	9.831
			(4.15)	(4.65)	(3.53)	(4.07)
	In arb	Not EoQ	1.010	0.907	3.771	2.897
			(4.26)	(6.40)	(3.96)	(3.53)
	No arb	EoQ	1.318	1.100	8.200	2.111
			(1.28)	(2.46)	(11.25)	(5.35)
	No arb	Not EoQ	0.284	0.169	0.724	0.847
			(1.28)	(2.62)	(2.34)	(2.07)
Dollar index						
	In arb	EoQ	0.078	0.071	0.389	0.461
			(2.92)	(3.13)	(6.89)	(2.78)
	In arb	Not EoQ	-0.018	0.002	-0.002	0.011
			(-1.33)	(0.26)	(-0.07)	(0.38)
	No arb	EoQ	0.010	0.004	-0.022	0.015
			(0.64)	(0.37)	(-0.35)	(0.15)
	No arb	Not EoQ	-0.024	-0.006	0.003	0.009
			(-2.01)	(-0.68)	(0.25)	(0.62)
Lagged dependent			-0.207	-0.061	0.018	0.044
			(-4.46)	(-1.36)	(0.25)	(0.56)
Obs.			1,648	1,648	1,631	1,408
Adj.R^2			0.13	0.10	0.12	0.11

Notes: The Table shows results from panel regressions of changes in CIP deviations (1-month and 1-week maturity) on FX swap order flow, across six different currencies, for the MMF reform period. CIP deviations are based on an arbitrage strategy funded in the U.S. commercial paper market for banks with either A-2/P-2 rating or high-rated banks with A-1/P-1-rating and measured in basis points. The constant (not reported) and error-correction terms (lagged level of CIP deviation) have constant coefficients across deviation regimes, while the other explanatory variables are allowed to have different effects, depending on whether a deviation exists or if it is in an end-of-quarter period. End-of-quarter effects start 1-week (1-month) before for a 1-week (1-month) tenor. Swap order flow is standardized by its standard deviation, while the broad dollar index return is measured in basis points. Robust t-statistics (cross-sectional clustering) are reported in parenthesis below coefficient estimates. Sample: April 2016 – June 2017.

Table A.1
Data sources and description

	Source	Code example	Tenors	Currencies	Comment
A. Unsecured money market rates					
Commercial Paper (CP)	TradeWeb via TR Eikon	YUSD3MCP=TWEB	1M, 3M	USD, EUR, GBP, JPY	Ratings[1]: W, Y, Z
Certificates of Deposit (CD)	Bloomberg	Extensive ISIN-search	1W-6M	USD	Trades
Interbank Deposit	TR TickHistory	USD3MD=,BID	1W-3M	All (USD, AUD, CAD, CHF, EUR, GBP, JPY)	High Freq
	TR Eikon	USD3MD=,BID	1W-3M	All	
IBOR	Bloomberg	US0003M INDEX	1W-3M	All (AUD[2])	
B. Risk-free interest rates					
Central bank deposits	Bloomberg	EECBDEPO INDEX		All	Example: ECB
Treasury bills	Bloomberg	USGG3M INDEX BID	3M	All	
Overnight Indexed Swaps (OIS)	TR TickHistory	GBP3MOIS=,ASK	1W-3M	All (AUD[3], CAD[3], CHF[3], GBP[3], JPY[3])	High freq
C. FX instruments					
Spot FX	TR TickHistory	EUR=D2,ASK		All against USD (AUD[4], CAD, CHF, EUR[4], GBP[4], JPY)	Trades, High freq
	Bloomberg	EURUSD CURNCY ASK		All	
Dollar index	St.Louis Fed FRED	DTWEXB		Broad index	
FX Swaps	TR TickHistory	EUR3M=,BID	1W-3M	All	High freq
	Bloomberg	EUR3M CURNCY BID			
FX Swaps (D3)	TR TickHistory	EUR3M=D3,BID	1W-3W	All	Trades, High freq
D. Other data					
Days to maturity	TR Eikon	Built-in function			
Interbank activity	St.Louis Fed FRED	IBLACBW027NBOG			
Assets under management	St.Louis Fed FRED	WMMFAMNA			
CP issuances by foreigners	St.Louis Fed FRED	FCPOFFS			
Foreign banks holding of JPY deposits	KPMG Foreign banks in Japan Survey	Several reports			

Notes: The Table gives an overview of data sources and instruments considered. The maximum range of tenors we have is 1-week (1W, or SW, Spot week), 2-week (2W), 3-week (3W), 1-month (1M), 2-month (2M), and 3-month (3M), with focus on 3-month horizon in text and 1-week and 1-month in appendix. The maximum available set of currencies includes the Australian dollar (AUD), the Canadian dollar (CAD), the Swiss franc (CHF), the euro (EUR), the pound sterling (GBP), and the Japansese yen (JPY). "TR" in the source-column is short for "Thomson Reuters." "D2" and "D3" in the code-example means sourced from Reuters D2000-2 and D3000-3, electronic limit order books for trading in FX markets. Superscript notes: 1: W = A-2/P-2; Y = A-1/P-1; Z = A-1+/P-1. 2: Not all tenors available for AUD. 3: Not all tenors available. For AUD, CAD and CHF, shortest is 1 month. 4: These currencies are base-currency vis-a-vis the USD, otherwise USD is base.

Supplementary Internet Appendix to accompany

Covered Interest Parity Arbitrage

A. Equations for LOOP and CIP calculations

Covered Interest Parity (CIP) is typically, in a simplified way, expressed as

$$1+r_d = \frac{1}{S}\left(1+r_f\right)F, \tag{OA.1}$$

where r_d and r_f are domestic and foreign interest rates, respectively, and S and F are spot and forward rates, expressed in units of domestic currency for a foreign currency, and the forward contract has the same maturity as the interest rates. This equation is obviously a simplification since it disregards that prices come with a bid-ask spread, ie. differ if one borrows (ask-rates) or lends (bid-rates), or buys (ask) or sells (bid) currency.

CIP is typically thought of as an arbitrage, i.e a self-financing round-trip. We can also use it to compare two borrowing (or lending) rates, in which case we are studying the Law of One Price (LOOP). Furthermore, one has to consider whether one takes the perspective of domestic borrowing, in which case one buys spot and sells forward, or vice versa in the case of foreign borrowing. LOOP is a weaker condition than CIP (Akram, Rime, and Sarno, 2009).

A.1. *CIP: Round-trip arbitrage*

Taking bid-ask prices into account, represented by b and a superscripts, respectively, CIP is *not* violated if the following conditions hold:

$$(1+r_d^a) \geqslant \frac{F^b}{S^a}(1+r_f^b), \tag{OA.2}$$

$$(1+r_f^a) \geqslant \frac{S^b}{F^a}(1+r_d^b). \tag{OA.3}$$

Using swap rates instead of forward rates, represented by $\overline{F^b - S^a}$ and $\overline{F^a - S^b}$ for bid and ask swap rates, respectively, then a positive arbitrage Dev is given by,

$$Dev^b > 0 \Rightarrow \overline{F^b - S^a} > S^a \frac{r_d^a - r_f^b}{1+r_f^b}, \tag{OA.4}$$

$$Dev^a > 0 \Rightarrow \overline{F^a - S^b} < S^b \frac{r_d^b - r_f^a}{1+r_f^a}, \tag{OA.5}$$

where the arbitrage superscript comes from the superscript on the forward leg of the swap (i.e, Dev^a

in the case of USDJPY means buying USD at the forward leg).[43]

We can rewrite this as a condition between actual and swap-based interest rates, the so-called cross-currency basis. On the bid-side:

$$\overline{F^b - S^a}\frac{1+r_f^b}{S^a} > r_d^a - r_f^b$$

$$\overline{F^b - S^a}\frac{1+r_f^b}{S^a} + 1 + r_f^b - 1 > r_d^a$$

$$\frac{\overline{F^b - S^a}}{S^a}\left(1+r_f^b\right) + \frac{S^a}{S^a}\left(1+r_f^b\right) - 1 > r_d^a$$

$$\left[\frac{S^a + \overline{F^b - S^a}}{S^a}\right]\left(1+r_f^b\right) - 1 > r_d^a \tag{OA.6}$$

Proceeding similarly for the ask-side gives the following two conditions for measuring profitable CIP deviation using cross-currency basis representation:

$$Dev^a > 0 \Rightarrow \left[\frac{S^b + \overline{F^a - S^b}}{S^b}\right]\left(1+r_f^a\right) - 1 < r_d^b, \tag{OA.7}$$

$$Dev^b > 0 \Rightarrow \left[\frac{S^a + \overline{F^b - S^a}}{S^a}\right]\left(1+r_f^b\right) - 1 > r_d^a \tag{OA.8}$$

A.2. *LOOP: One-way arbitrage*

The law of one price can be violated either for borrowing rates (ask) or lending rates (bid). Strictu senso, this is not an arbitrage as it is only relevant for those that have a borrowing or lending need. If we take the perspective of borrowing rates, these are *not* in violation if the following holds:

$$Ask \;:\; 1+r_d^a \leq \frac{1}{S^b}\left(1+r_f^a\right)F^a$$

$$Bid \;:\; 1+r_f^a \leq S^a\left(1+r_d^a\right)\frac{1}{F^b}$$

The first condition says that it is cheaper to finance in the domestic market than to shop around to borrow abroad and swap into domestic currency. The second equation states the same, but from the perspective of the foreign market.

[43] Rewrite the no-arbitrage CIP condition as the forward rate, $\frac{(1+r_d^a)}{(1+r_f^b)}S^a \geqslant F^b$, and subtract S^a from both sides to get the condition above.

Expressed with swaps, these conditions become:

$$Ask: \frac{r_d^a - r_f^a}{1+r_f^a} S^b \leq \overline{F^a - S^b}$$
$$Bid: \overline{F^b - S^a} \leq S^a \frac{r_d^a - r_f^a}{1+r_f^a} \tag{OA.9}$$

These equations can be rearranged to express the condition as difference between actual and swap-implied interest rates, i.e. the basis. At the ask-side,

$$\frac{r_d^a - r_f^a}{1+r_f^a} S^b \leq \overline{F^a - S^b}$$
$$r_d^a \leq \frac{1+r_f^a}{S^b} \overline{F^a - S^b} + r_f^a$$
$$r_d^a \leq \left[\frac{S^b + \overline{F^a - S^b}}{S^b} \right] \left(1+r_f^a\right) - 1$$
$$r_f^a < \left(1+r_d^b\right) \frac{S^b}{S^b + \overline{\overline{F^a - S^b}}} - 1. \tag{OA.10}$$

For the bid side:

$$r_d^a < \left[\left(\frac{S^a + \overline{F^b - S^a}}{S^a} \right) \left(1+r_f^b\right) - 1 \right] \tag{OA.11}$$

A.3. Adding market conventions

There are several issues that have to be taken into account when such conditions as stated above are used in calculations based on actual market data. We list them here:

1. Swaps are not priced as forward price minus spot price, but rather in the units of the smallest decimal of the spot price (so-called pips). For example, if $F = 1.1001$ and $S = 1.000$, then the quoted swap is 1 (and not 0.0001). So quoted swap prices must be divided by 10 to the power of the number of decimal points. For most currencies this is 4, while for JPY it is 2.

2. Interest rates are quoted in percentage points and not as a share of 100 as above. All the 1s in the above equations must therefore be replaced by 100.

3. Interest rates are quoted as annual rates, and not for the maturity time-horizon. Hence, the interest rates must be corrected for this by multiplying by number of days to maturity divided

by number of days in a year, $D/YEAR$. Most countries calculate with 365 days in a year, except the UK which uses 360. Days to maturity must respect that both markets are open, and the interested reader is referred to Akram, Rime, and Sarno (2008) for details. Bloomberg and other financial services can provide the exact days for any date and currency pair.

When applied to the CIP basis at the bid, the condition then becomes:

$$Basis^b_{CIP} = -r^a_d + \left[\left(\frac{S^a + \overline{F^b - S^a}/10^4}{S^a} \right) \left(100 + r^b_f \frac{D}{360} \right) - 100 \right] \frac{360}{D}. \qquad \text{(OA.12)}$$

B. Rollover risk in CIP arbitrage with OIS contracts

This section provides further details on the rollover risk inherent in CIP arbitrage involving OIS contracts. We argued in the main text that the main reason why OIS-based CIP deviations do not reflect riskless arbitrage opportunities is term funding liquidity premia. But relying on OIS contracts in CIP arbitrage exposes the arbitrageur to rollover risks as well. This can be a further factor in impeding arbitrage activity.

Implementing a CIP arbitrage trade based on OIS contracts is fairly complicated (illustrated by OA.9). We repeat the sequence of trades here for convenience:

1. Borrow funds overnight (O/N) in the borrowing currency,
2. Roll over the O/N loan daily over the preferred maturity and hedge the interest rate risk by paying the (fixed) OIS rate of the same maturity,
3. Buy the lending currency spot, hedging the exchange rate risk by selling the lending currency forward at the date when the OIS matures,
4. Invest the lending currency O/N,
5. Roll over the O/N investment and hedge the interest rate risk by receiving the OIS rate in the lending currency.

[Insert Figure OA.9 about here]

The issue of rollover risk is best illustrated by looking at the difference between quoted O/N interbank deposit rates and the underlying O/N rate in the OIS contract for EUR and USD.[44] If an arbitrageur seeks to exploit any alleged cross-currency basis widening based on OIS rates, she has to constantly borrow USD in the US O/N market and place EUR-denominated funds in the EUR area O/N market. This may have to be done at different rates than the weighted average of the money market transactions that are used for the fixing of the underlying O/N rate in the OIS contract.[45]

It is well-known, for instance, that the effective Federal funds rate that constitutes the underlying interest rate in USD OIS contracts, is heavily affected by transactions involving Government-sponsored Entities (Fannie Mae, Freddie Mac and 11 Federal Home Loan Banks) that can transact in the Fed funds market, but that do not have access to the Fed's deposit facility (Bech and Klee, 2011). The Fed funds market may deviate from the O/N eurodollar market, a development that has encouraged the Federal Reserve Bank of New York to develop an alternative benchmark rate (Overnight Bank Financing Rate). This rate relies on eurodollar transaction data (see, e.g., Duffie and Krishnamurthy, 2016).

[Insert Figure OA.10 about here]

Figure OA.10 illustrates the rollover risk in OIS-based CIP arbitrage arising from the incongruence of the evolution of actual O/N borrowing rate faced by the arbitrageur and the movement of the underlying floating O/N rate in the OIS contract. As can be gleaned from the graph, this spread can widen out significantly at times and can be quite volatile, suggesting that rollover risk can be quite material in discouraging OIS-based CIP arbitrage.[46]

C. CIP arbitrage with repo contracts

As discussed in the main text, it has also been common to express alleged CIP arbitrage opportunities drawing on GC repo rates. Figure OA.11 illustrates the mechanism of using the repo market in CIP arbitrage.

[44]The underlying O/N rates in the EUR and US OIS contracts are EONIA and the effective Fed funds rate, respectively.

[45]Griffoli and Ranaldo (2010) also point this out, but assume in the remainder of their analysis that this spread is negligible.

[46]The GFC is a primary example of evaporating funding liquidity characterised by a shortening of the maturity of funding, where it became highly expensive, and even virtually impossible, to roll over O/N funding. Instead of providing reserves in the O/N market, banks were hoarding reserves and arbitrageurs (hedge funds and proprietary trading desks in banks) found it difficult to even obtain O/N funding.

[Insert Figure OA.11 about here]

The following example may shed further light on our argumentation in the text that CIP deviations based on GC repo rates reflect cross-currency differences in the total costs of funding the collateral. Imagine a bank with an initial portfolio endowment of both US and German Treasuries. These assets are unencumbered and obviously ultimately funded by unsecured borrowing. The bank can repo out the US Treasuries and obtain cash. When encumbered through a repo, the US Treasuries serve as a vehicle to be exposed to potential interest rate risk, but cannot generate any more cash during the term of the repo. This means that it makes little difference to the bank whether it conducts a repo or sells US Treasuries in order to obtain the necessary USD for the trade. When the Treasuries are sold, it is clear that the bank is left with cash financed by unsecured borrowing. The shadow cost of encumbering the collateral is the difference between the unsecured borrowing and the repo rate, plus the cost of a potential haircut and posting variation margin. The bank conducts an FX swap, receives EUR and engages in a reverse repo, receiving German Bunds. The bank can now raise cash in EUR by re-using its euro-denominated assets received in the repo, but cannot raise USD via the euro-denominated asset without going through the FX swap market again. Thus, the new euro-denominated assets are effectively financed by unsecured USD funding. This simple example shows that the secured funding cost is not an expression of the marginal funding cost in the CIP arbitrage trade based on repo contracts.

Special repo. When testing for the existence of arbitrage opportunities based on repo rates, it is necessary to move beyond GC repo rates. A special repo needs to be considered where the arbitrageur delivers and receives collateral denominated in the same currency in both the borrowing and the investment currency. This does not alter the currency composition of the liquidity portfolio of the arbitrageur, and hence allows a comparison of "apples with apples". The interest rate quoted in a special repo, however, can be very different from that in a GC repo. The issue is exacerbated when the relative term funding premiums between the two currencies are different.

Data on special repos are rare and difficult to obtain. We asked for a cross-currency OTC repo quote from a high-rated dealer via Norges Bank's money market desk. The dealer responded by saying that such a deal would have been priced based on the FX swap price. This means that the dealer would need to add the cost of delivering a security denominated in the currency with a high funding liquidity premium equal to the cost of swapping cash into the same currency. This would obviously effectively eliminate any profit from the CIP trade.

Rehypothecation. There may be situations, however, where market participants are able to use collateral where their own unsecured funding cost is not the correct measure of the full marginal cost. This applies for example to custodians and a practice called rehypothecation. Rehypothecation means that the custodian has an agreement with the legal owner of the asset to use the collateral against a fee. This was common practice among U.S. custodians before 2008, but legal issues connected to rehypothecation and regulatory initiatives have reduced both the demand for and supply of this business in recent years. In any case, the fee the custodian has to pay must be incorporated in the cost of applying the CIP trade.

D. How do banks price funds internally?

An important concept of how banks determine the "internal price" when allocating funds across different divisions is *funds transfer pricing* (FTP). The treasury division is responsible for the bank's funding, its liquidity management and the internal pricing of funds to its different operations. One can think of the treasury division as a "bank within the bank": it buys funds from the divisions managing the liability side of the bank and sells funds to the divisions that invest in assets. The most commonly used method currently considered by practitioners is called matched-maturity funds transfer pricing.

The basic goal of FTP is to transfer interest rate risk and liquidity risk to a central location (the treasury unit) and make the booked income of the remaining units of the bank immune against these risk factors. Matched-maturity funds transfer pricing implies that the prices at which the treasury buys funds from its deposit-taking units and the prices it charges for funds transferred to units investing in banking assets are related to the cost of obtaining the funds. This means that the internal price also reflects the associated balance sheet costs for a given maturity.

To accomplish this task, the treasury unit constructs an interest rate curve, determining the funds transfer price for the full maturity spectrum. This curve incorporates the marginal cost of using funds across maturities. The use of a marginal cost interest rate curve enables the treasury unit to maintain all liquidity risk within the treasury department and price this risk accordingly (arising from maturity transformation).[47] Hence, the corresponding interest rate curve determines the appropriate price at which the treasury unit buys and sells funds such that the business units are left with the net interest margin arising from (i) the funding spread between deposit rates faced by the bank's customers (liability side) and the internal price, and (ii) the spread between the internal

[47] Liquidity transfer pricing is an integral part of funds transfer pricing (see Grant (2011)).

price and the return on the banking assets (asset side).

The crucial part of FTP is to construct the interest rate curve based on the marginal funding costs faced by the bank in a way that also reflects the balance sheet cost. A crude way of doing this is to use interbank deposit rates for tenors below one year and the Interest Rate Swap (IRS) curve beyond that.[48] The difference between the market swap curve based on interbank deposit rates and the final FTP curve determines the term structure of the funding liquidity premium. The reason for using deposit rates in FTP is that they are regarded as a reasonable proxy for the marginal cost of using funds for banks.

Globally active banks need to create a FTP curve in each of the currencies they are operating in. For example, a bank may establish a full interest rate curve in its main funding currency and then rely on the pricing in the FX swap market to create implied interest rate curves in the rest of the operating currencies. Alternatively, the bank could calculate a fully independent curve in each of the currencies. Regardless of the approach taken, the internal price of funds in different currencies has to be consistent with the implied interest rate one can achieve through the FX swap market. In case of a discrepancy, internal business units may otherwise exploit the inconsistency.[49]

Funds transfer pricing and the law of one price. The discussion above has major implications for investigating the law of one price in international money markets. As laid out above, the internal pricing of funds by banks needs to be closely aligned with the law of one price.[50] Interbank deposit rates reflect the general interest rate level in a currency, the term funding liquidity premium, the credit risk premium of the quoting bank, and the balance sheet cost of using additional funds. Interbank deposit rates thus exactly capture what banks' funds transfer price ought to represent as well. One may therefore expect that there is a tight empirical relationship between interbank deposit rates and the funds transfer price.

[48]It is more precise to construct the FTP curve by relying on the bank's own fixed-rate funding cost, stripped down to variable-rate marginal funding cost by an internal interest rate swap.

[49]For example, if the treasury pays business units more for currency A than it implicitly charges for the funds in currency B swapped into currency A by conducting an FX swap, business units may have an incentive to borrow currency B, conduct an FX swap in the market and sell currency A back to the treasury unit.

[50]Of course, the treasury department may be in a position to look for the relative value of funding in different currencies. One should also point out that the exact implementation of FTP may vary across banks. That said, the main principles remain largely intact.

E. Construction of high-frequency data

We primarily use high-frequency data for the creation of daily time series for FX swap order flow and spot order flow. Results based on high-frequency intraday analysis of CIP deviations when funded in interbank deposits (focus of previous drafts) are available upon request, but are omitted here as interbank deposits are no longer a vibrant source of funding. Results are quite similar to the results based on Commercial Paper (CP) due to so-called *funds transfer pricing* (FTP), which is further elaborated in Online Appendix D.

We follow Akram, Rime, and Sarno (2008) closely and collect high-frequency data for interbank deposits rates, OIS rates, FX spot and FX swaps, as shown in the overview in Table A.1. All high-frequency data are timed to the thousandth of a second (millisecond) and are from 2005 until June 2017. We merge all data to the exact time and fill in with previous prices if an instrument does not have an updated quote in a particular millisecond.

Spot exchange rates are taken from the Reuters D2000-2 Electronic Limit Order Book, one of the primary wholesale trading platforms for trading FX Spot. The D2000-2 is an inter-dealer platform, which is mostly used by market makers to offload inventory positions from trades with end-users. This market thus performs an important risk-sharing function.

We use FX swaps instead of forwards because this is how sophisticated participants in interbank markets implement forward transactions. For FX swaps, we rely on two different sources, indicative quotes and data from the FX swap part of the electronic limit order book Reuters D2000-2 (this part is often labelled D3000-3). Table OA.III in the Online Appendix compares the two. The indicative quotes are our preferred high-frequency source since they are quoted for all maturities, updated more frequently, and the bid-ask spreads in the two segments are fairly close to each other.

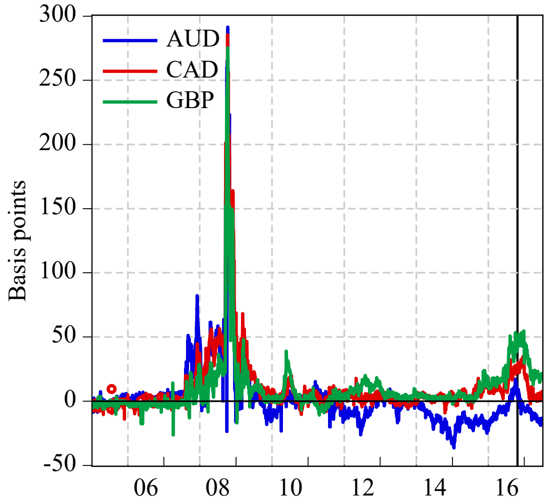
[Insert Table OA.III about here]

The deposit quote on the ask side is an indication of the rate at which the quoting bank is willing to lend funds to another bank (i.e. placing deposits). The bid-quote is an indicative price for borrowing funds (i.e. accepting deposits) from another bank. Both bid and ask rates are quoted continuously throughout the day. OIS is a derivative, but the quote on the ask-side can be interpreted as the borrowing rate.

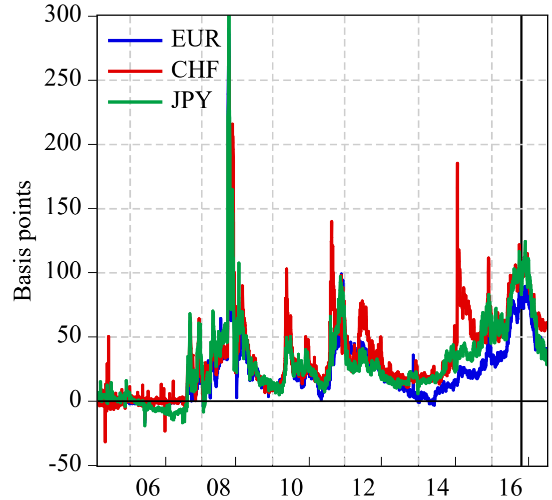
We create measures of order flow for spot and FX swaps based on transactions on the electronic limit order books. By matching transaction prices with the prevailing best bid and ask quotes, we can determine the sign of the trade, positive (1) for buyer-initiated trades (at ask) and negative (-1) for seller-initiated trades. For FX swaps we construct the order flow to measure the net number of buyer/seller-initiated trades in USD in the spot leg of the swaps. Hence it serves as a proxy of demand and supply imbalances in the swap market, available at high frequency. Daily aggregates are created based on weekdays between GMT 01:00-18:00 and only for active trading days.

Figure OA.1
Cross-currency basis with OIS rates. 3-month maturity

(a) AUD, CAD, GBP

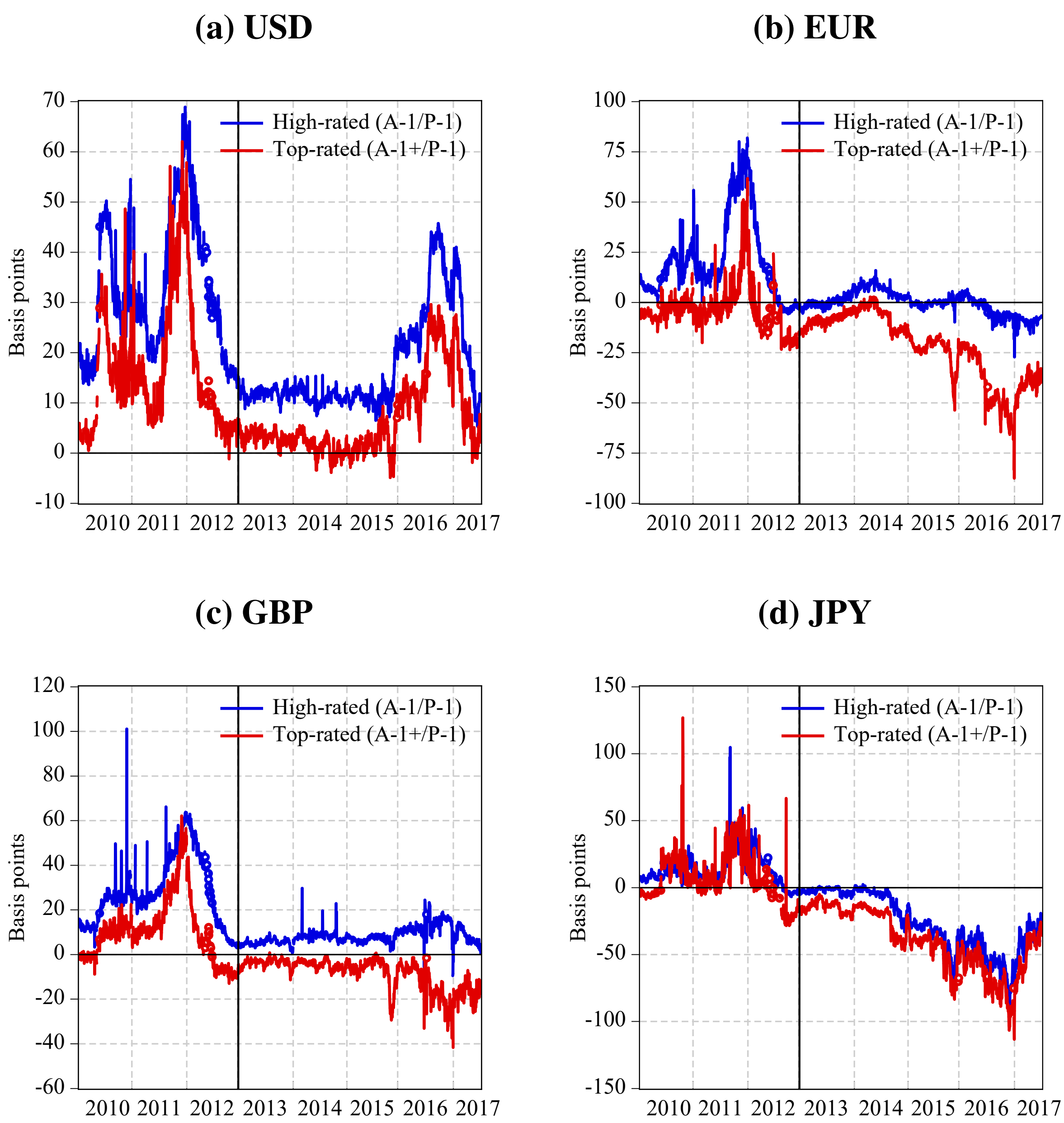


(b) EUR, CHF, JPY



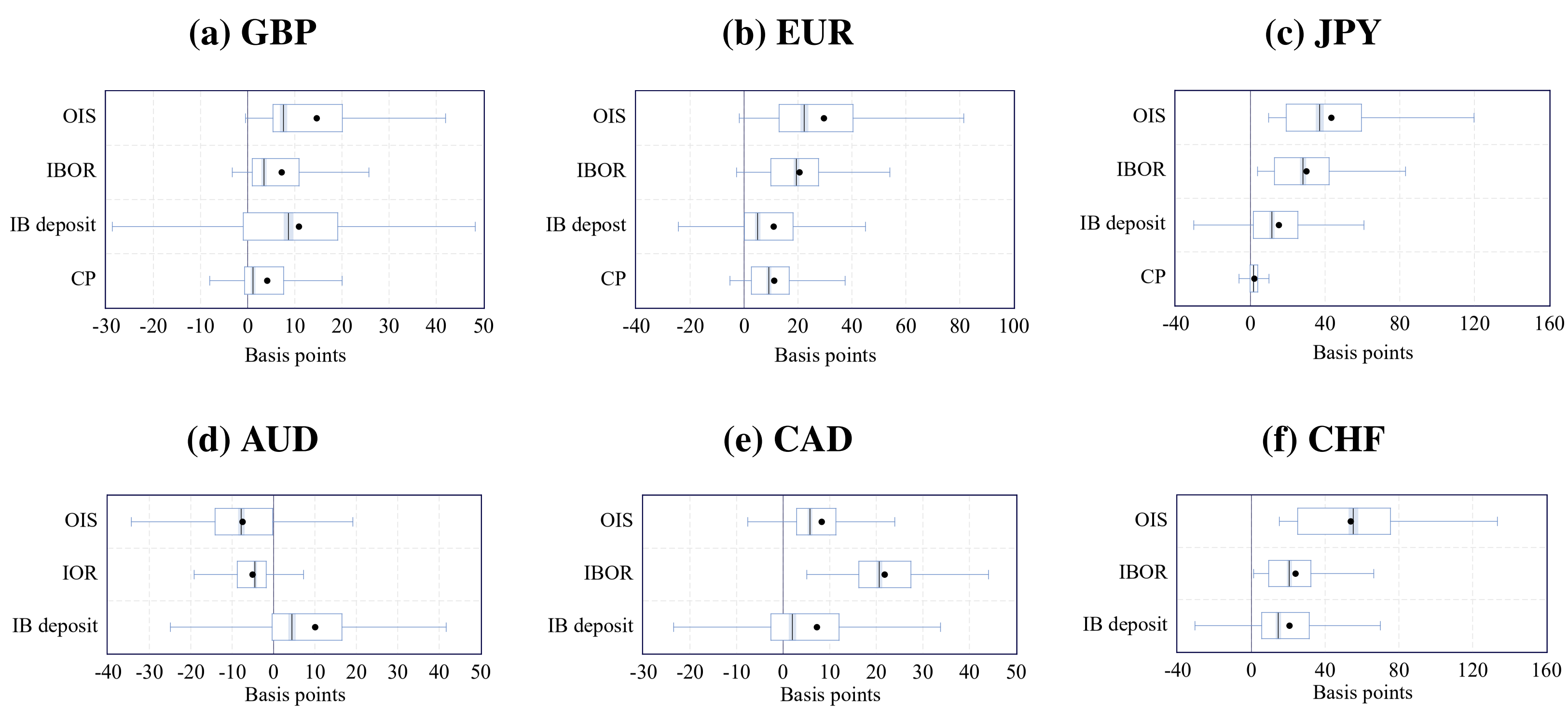
Notes: The Figure shows the evolution of profits from roundtrip cross-currency basis trades (measured in basis points) involving USD borrowing (USD interest rate at the ask rate), using 3-month OIS rates. All legs of the roundtrip cross-currency trade (rates and FX swaps) are adjusted for bid-ask spreads (as described in the text). Panel (a) shows trading profits for AUD, CAD and GBP, while Panel (b) depicts the corresponding profits for EUR, CHF and JPY. Axis capped at 300bp for readability. The maximum was just above 400bp for JPY during October 2008. The vertical line indicate October 14, 2016, the date of the implementation of the US Money Market Fund reform.

Figure OA.2
CP-OIS spreads (3-month maturity)



Notes: The Figure depicts the evolution of the spread between the 3-month Commercial Paper (CP) rate over the 3-month OIS rate for two rating groups and four currencies. Rating A-1/P-1, which is used throughout the paper, is compared to the even better rating A-1+/P-1. The sample runs from 2010 to June 2017. The vertical line at January 2013 indicate the beginning of the less turbulent period that is the focus of the current paper.

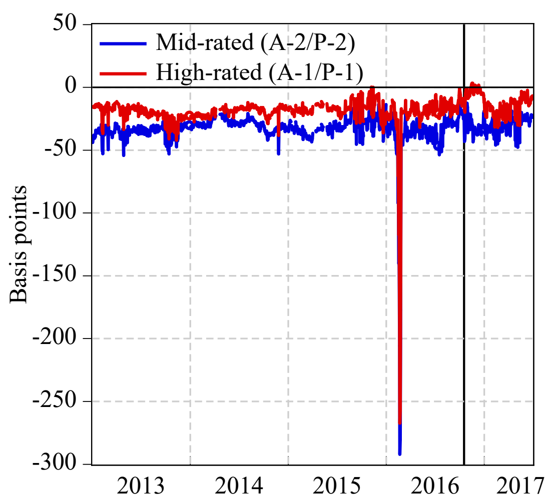
Figure OA.3
LOOP deviations for different money market rates (3-month maturity)



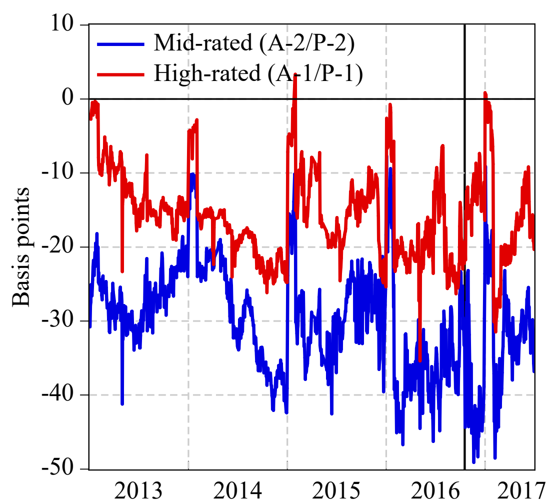
Notes: The Figure shows box plots of LOOP deviations for different 3-month money market rates. The depicted LOOP deviations compare the direct FCU rate and the implied rate by swapping from USD. For ease of exposition, the average across the currencies for which we have CP rates (EUR, JPY, and GBP) is shown and LOOP deviations for CP rates are averaged across rating-categories. LOOP violations are measured in basis points. Elements of the box plot are as follows: the staples (end of straight line) represent value of last data point; the box itself represents the first and third quartile; inside the box, the mean is represented by a dot, while the median is represented by a line; the shaded area around median represents 95% confidence interval. Sample: January 2013 – June 2017.

Figure OA.4
Risk-free 3-month CIP arbitrage opportunities for global banks. Average over AUD, CAD, and GBP.

(a) Invest in T-bills



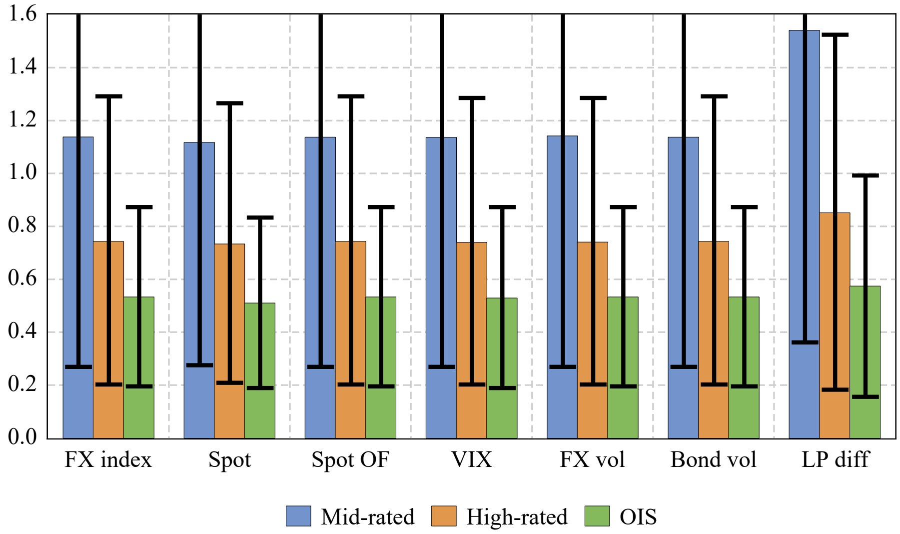
(b) Invest in CB deposits



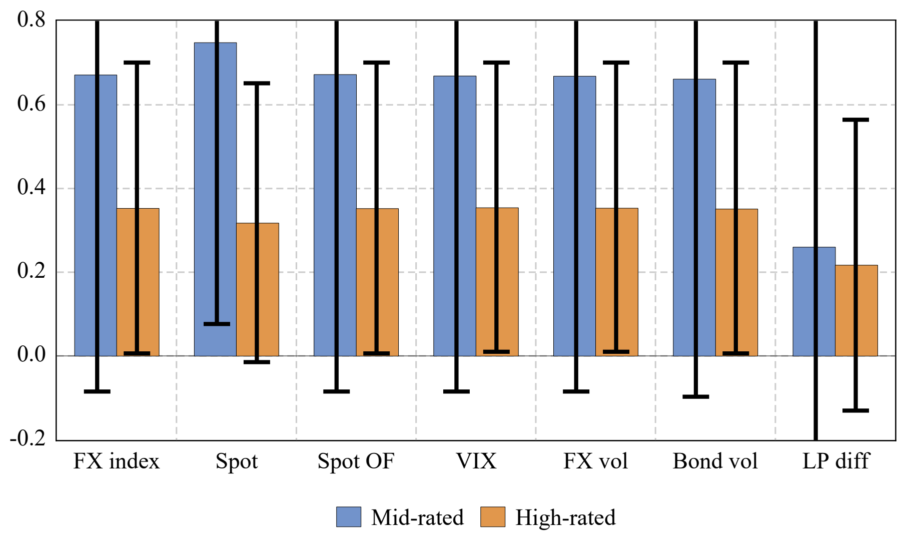
Notes: The Figure shows risk-free CIP arbitrage profits for global banks when funded via the issuance of USD commercial paper, swapping into foreign currency, and investing the funds in the foreign Treasury bills (Panel (a)) or central bank deposits (Panel (b)). Funding rates differ for mid-rated banks (A-2/P-2) and high-rated banks (A-1/P-1). The vertical lines indicates October 14, 2016, the date of the implementation of the US Money Market Fund reform. Sample: January 2013 – June 2017.

Figure OA.5
Impact of FX swap order flow for alternative specifications (3m)

(a) Central bank deposit investment and OIS-basis



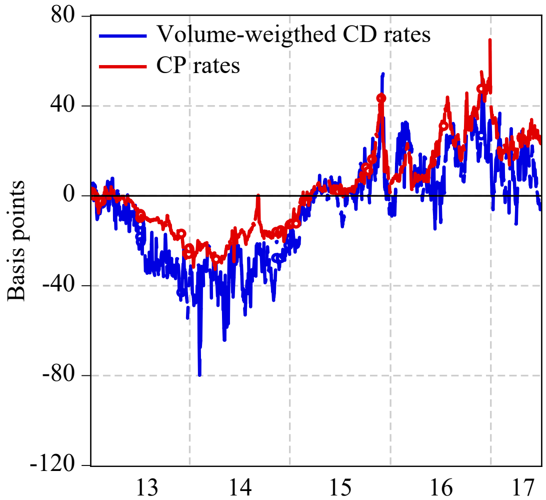
(b) Treasury bill investment



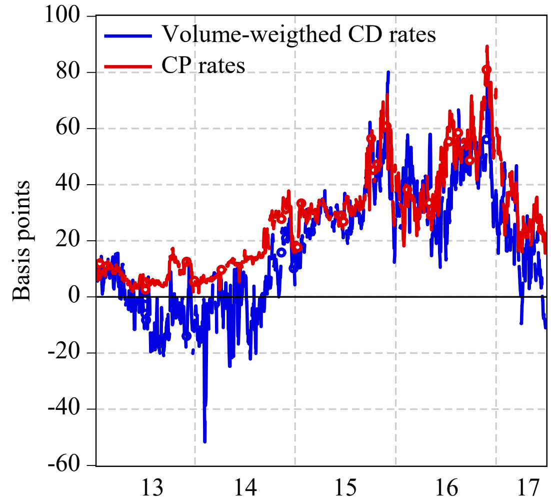
Notes: The Figure shows the impact of (standardized) swap order flow on CIP arbitrage profits, conditioned on being in a positive arbitrage state, for different model specifications. Vertical lines indicate $\pm 2 \times$ coefficient standard errors, which are symmetric but truncated at top and bottom if they reach outside graph area. Panel (a) shows alternatives with CIP deviations using central bank deposits as investment (as in c), or OIS basis. Panel (b) shows results for T-bills as the investment-leg in the CIP-arbitrage. The seven alternative models are as follows (from left): (i) Using a broad FX index (for panel (a) same as 3); (ii) replacing the FX index with bilateral spot exchange rates; specifications (iii)-(vii) adds different variables to the benchmark model in (i), like VIX, FX volatility represented by the VXY index, bond market volatility represented by MOVE index, and our measure of liquidity premium differentials. Sample for estimation: January 2013 – June 2017.

Figure OA.6
CIP arbitrage profits using CP rates vs. volume-weighted CD rates (3-month maturity)

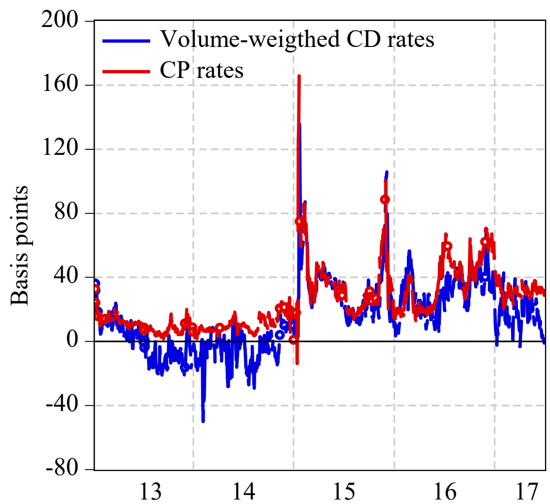
(a) EUR



(b) JPY



(c) CHF



Notes: The Figure compares 3-month CIP arbitrage profits (in basis points) when investing in central banks deposits, for high-rated banks (A-1/P-1) using different sources of funding. The comparison is between funding either using CP rates or (5-day moving average of) the volume-weigthed CD rates faced on the issue date. Sample: Jan 2010 – July 2017.

Figure OA.7
Two balance sheet scenarios

(a) Balance sheet reduction via FX swaps seen from a EUR-rich bank (assuming EURUSD FX rate is 1)

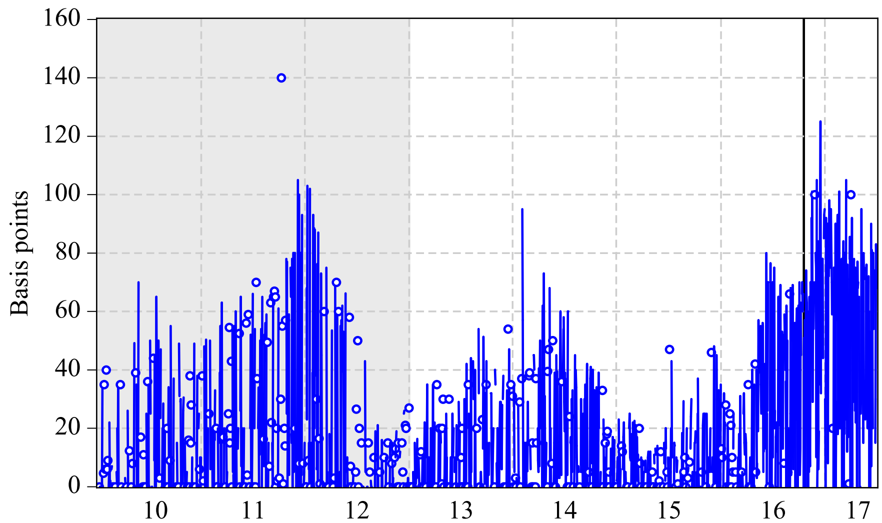
Assets	Liabilities		Assets	Liabilities		Assets	Liabilities
		FX swap:			Pay down		
Cash €100	€100 Deposit	-€100/	**Cash $100**	€100 Deposit	ST debt	**Cash €0**	€100 Deposit
Loan $100	$100 ST. debt	+$100	Loan $100	$100 ST. debt	in $	Loan $100	**0 ST. debt**
Total €200	€200 Total	⇒	Total €200	€200 Total	⇒	Total €100	€100 Total

(b) USD-financed arbitrage

Assets	Liabilities		Assets	Liabilities		Assets	Liabilities
		Borrow			FX swap:		
Cash $0	$100 Deposit	to do	**Cash $100**	$100 Deposit	-$100/	**Cash €100**	$100 Deposit
Loan $200	$100 ST. debt	arb	Loan $200	**$200 ST. debt**	+€100	Loan $200	$200 ST. debt
Total $200	$200 Total	⇒	Total $300	$300 Total	⇒	Total $300	$300 Total

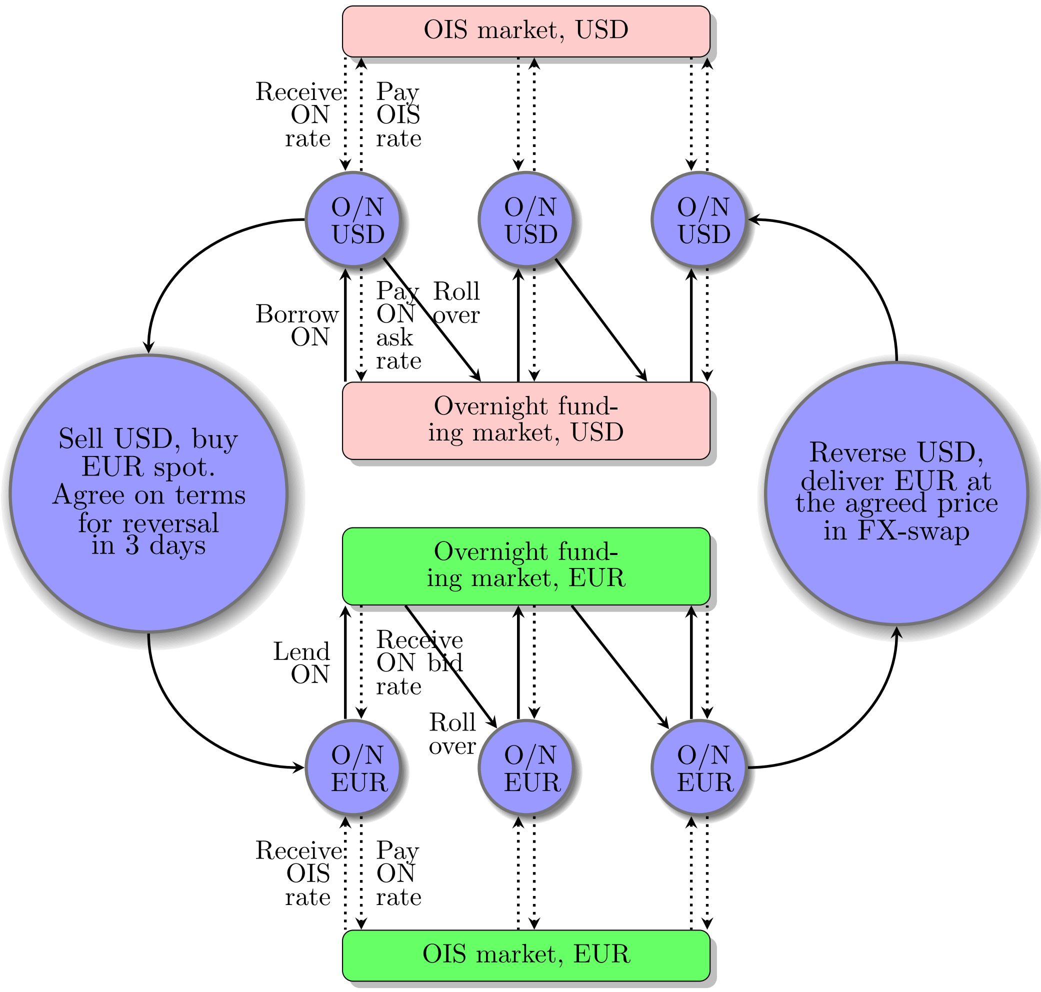
Notes: Panel (a) shows balance sheet impact by swapping from EUR to USD to reduce debt for the purposes of window-dressing. Panel (b) shows balance sheet impact by increasing USD debt to open an arbitrage position.

Figure OA.8
USD funding cost dispersion



Notes: The figure shows the range of funding costs for 3-month funding in the CD market for high-rated banks (A-1/P-1). The shaded area indicates the period of financial turmoil until the end of the euro crisis in 2012. The vertical line indicates October 14, 2016, the date of the implementation of the US Money Market Fund reform. Sample: 2010– June 2017.

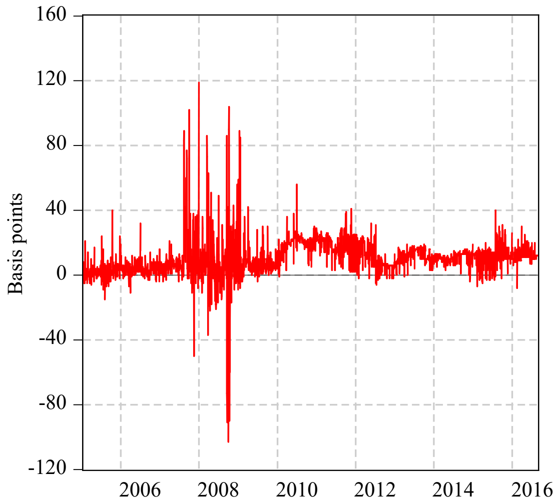
Figure OA.9
Using OIS contracts in CIP arbitrage



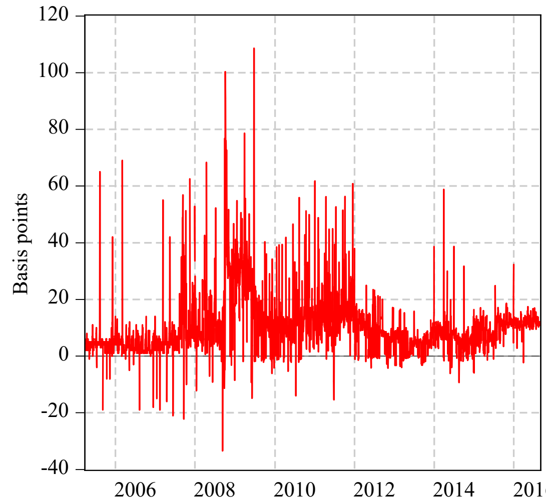
Notes: The graph shows the mechanics involved in using OIS contracts for CIP arbitrage. Solid lines represent transactions while dashed lines are interest rate payments. In the OIS, the fixed rate is not paid or received every day. It is a fixed rate where the net difference between the average of the floating rate and the fixed rate is settled on the termination date of the contract.

Figure OA.10
Roll over risk in OIS-based CIP arbitrage

(a) USD

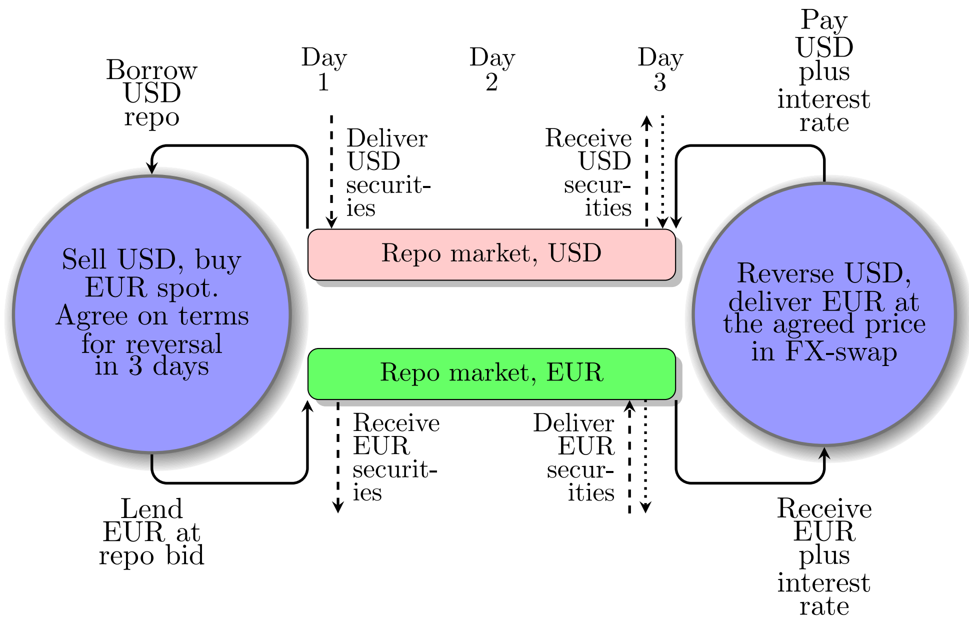


(b) EUR



Notes: The Figure show difference between overnight rates and the underlying overnight rate in the OIS contract measured in basis points. For USD, the underlying rate is the effective Fed funds rate, while for EUR it is the EONIA rate. The graphs show borrowing in USD (overnight ask rate minus effective Fed funds) in Panel (a) and lending in EUR (EONIA minus overnight bid rate) in Panel (b).

Figure OA.11
Using repo contracts in CIP arbitrage



Notes: The Figure shows the mechanics involved in using repo contracts for CIP arbitrage. Solid lines represent transactions, while dashed lines depict interest rate payments/security transfers.

Table OA.I
Comparison of money market spreads across currencies. 1-week and 1-month maturity

	Mean	Median	Std. Dev.	Obs.
		A: IBOR interbank rates		
1-month				
AUD	9.71	10.50	7.55	1,173
CAD	28.49	25.40	7.39	1,130
CHF	-17.51	-23.20	13.36	1,137
EUR	1.52	2.40	3.37	1,150
GBP	5.07	4.92	2.00	1,137
JPY	0.62	1.30	2.96	1,137
USD	6.66	6.30	2.37	1,136
1-week				
CAD	-0.66	-0.50	0.25	1,174
EUR	-1.87	-2.00	2.55	1,150
GBP	2.89	2.67	1.61	1,137
JPY	-0.95	-0.49	3.00	1,137
USD	2.22	2.09	1.82	1,137
		B: Interbank deposit rates		
1-month				
AUD	35.03	34.40	17.89	1,173
CAD	18.84	15.00	12.66	1,174
CHF	-11.53	-10.00	19.56	1,174
EUR	4.33	3.50	4.94	1,174
GBP	16.30	16.53	8.44	1,174
JPY	-0.05	3.60	11.28	1,174
USD	18.68	15.20	11.80	1,173
1-week				
AUD	23.45	22.50	16.56	1,173
CAD	14.31	12.00	13.06	1,174
EUR	2.16	1.20	5.22	1,174
GBP	9.72	7.70	5.36	1,174
JPY	-0.14	1.90	18.74	1,174
USD	12.59	12.70	7.04	1,174

Notes: The Table presents summary statistics for money market spreads across currencies. Panel A presents descriptive statistics on the difference between various interbank funding rates with a 3-month tenor and OIS rates, ie. $i^j - i^{OIS}$, $j \in \{\text{deposit, IBOR}\}$. All rates are measured as ask (offer) rates and mean, median and standard deviation of spreads are expressed in basis points. Sample: January 2013 – June, 2017.

Table OA.I
(Continued) Comparison of Commerical Paper (CP) spreads across currencies. 1-week and 1-month maturity

	Mean	Median	Std. Dev.	Obs.
		C: Commercial paper		
		Mid-rated banks (A-2/P-2)		
1-month				
EUR	-3.84	-1.60	7.75	1,102
GBP	4.50	4.60	4.13	1,103
JPY	-22.65	-18.18	20.94	1,045
USD	13.37	12.20	6.67	1,099
1-week				
EUR	-5.80	-6.10	5.24	1,070
GBP	-0.54	-0.20	4.25	1,093
JPY	-9.34	-6.48	12.55	368
USD	8.98	6.90	10.60	1,092
		High-rated banks (A-1/P-1)		
1-month				
EUR	-10.41	-9.50	6.58	1,106
GBP	-4.04	-2.70	5.56	1,103
JPY	-38.50	-29.26	36.31	1,099
USD	4.27	3.90	3.33	1,099
1-week				
EUR	-17.47	-14.60	20.85	998
GBP	-10.15	-6.60	21.33	957
JPY	-37.35	-25.90	74.68	924
USD	-0.96	-0.60	2.88	1,052

Notes: The Table presents summary statistics for money market spreads across currencies. Panel B provides summary statistics for the difference between 3-month commercial paper (CP) rates and OIS rates across two different rating categories, high-rated (A-1/P-1) and mid-rated (A-2/P-2). All rates are measured as ask (offer) rates and mean, median and standard deviation of spreads are expressed in basis points. Sample: January 2013 – June, 2017.

Table OA.II
Descriptive statistics: Risk-free investment vehicles in CIP arbitrage (2013-June 2017)

A. T-bills

	Mean	Median	Stdev	Obs
AUD	25.97	14.55	92.13	339
CAD	-4.94	-5.20	4.87	1,146
CHF	-2.35	2.45	16.11	1,125
EUR	-10.81	-6.55	11.51	1,165
GBP	1.47	1.12	5.86	1,016
JPY	-7.58	-5.29	9.13	755
USD	-10.81	-10.31	4.72	1,173

B. Central bank deposits

	Median	Ave.change	#change	June 2017
AUD	2.25	-0.25	6	1.50
CAD	0.75	-0.25	2	0.50
CHF	0.75	—	0	0.50
EUR	-0.20	-0.10	4	-0.40
GBP	0.50	-0.25	1	0.25
JPY	0.10	-0.20	1	-0.10
USD	0.25	0.25	4	1.25

Notes: The Table presents summary statistics for risk-free investment vehicles in risk-free CIP arbitrage. Panel A presents descriptive statistics on the difference between 3-month T-bill rates and OIS rates, ie. $i^{TB} - i^{OIS}$. Panel B provides summary statistics on the remuneration on central bank deposit facilities. All T-bill rates are measured as ask (offer) rates. The SNB (CHF) and BoJ (JPY) have a tiering structure for their deposit rates, meaning that not all reserves are remunerated at the same rate. Sample: January 2013 - June 2017.

Table OA.III
Liquidity characteristics of the FX swap market

	Tenor	Average # Quotes		Average Spread	
		Indicative	Tradeable	Indicative	Tradeable
AUD	1W	2742.75	11.38	0.215	0.145
	2W	2515.88	27.27	0.307	0.183
	3W	2616.23	55.23	0.389	0.185
CAD	1W	1935.86	5.68	0.264	0.154
	2W	1853.90	2.73	0.378	0.217
	3W	1431.16	2.56	0.509	0.256
CHF	1W	2356.58	6.02	0.293	0.182
	2W	2158.89	3.42	0.366	0.314
	3W	1948.19	2.98	0.532	0.337
EUR	1W	2587.97	20.85	0.158	0.098
	2W	2206.16	11.13	0.215	0.228
	3W	1305.15	8.75	0.285	0.294
GBP	1W	2069.01	7.65	0.188	0.159
	2W	1492.14	4.17	0.279	0.271
	3W	1274.88	3.82	0.333	0.300
JPY	1W	2057.12	9.50	0.146	0.153
	2W	2207.80	5.53	0.241	0.274
	3W	1382.40	4.48	0.278	0.372

Notes: The Table presents the daily average number of quotes and daily average bid-ask spread for indicative and tradeable FX swaps. FX swap points are expressed in pips, i.e. the difference between the spot and forward rate. One pip is the 4th decimal in the spot rate for currencies, except JPY, which uses the 2nd decimal. Overnight hours and weekends are excluded. Sample: 2005 — December 10, 2015.

Table OA.IV
Roundtrip cross-currency basis arbitrage with OIS rates. 3-month maturity

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
	Direction	Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
AUD	$FCU \Rightarrow USD$	7.9	9.5	68	57	847	2.1	9.2	65	39	326
	$USD \Rightarrow FCU$	-12.3	9.3	13	7	847	-6.2	7.7	24	15	325
CAD	$FCU \Rightarrow USD$	-8.1	4.5	0	0	848	-17.2	9.7	0	0	326
	$USD \Rightarrow FCU$	3.0	4.4	79	51	848	12.4	9.6	99	88	325
CHF	$FCU \Rightarrow USD$	-34.0	26.9	0	0	848	-89.4	19.6	0	0	326
	$USD \Rightarrow FCU$	25.1	24.8	100	100	848	80.3	18.6	100	100	325
EUR	$FCU \Rightarrow USD$	-19.2	10.6	0	0	846	-60.1	17.8	0	0	326
	$USD \Rightarrow FCU$	15.4	10.4	97	90	846	57.6	17.3	100	100	325
GBP	$FCU \Rightarrow USD$	-8.3	4.8	0	0	847	-33.7	12.9	0	0	326
	$USD \Rightarrow FCU$	3.9	4.6	99	85	848	26.0	12.4	100	100	324
JPY	$FCU \Rightarrow USD$	-25.3	16.9	0	0	848	-80.1	24.3	0	0	326
	$USD \Rightarrow FCU$	22.2	16.4	100	100	848	74.5	24.2	100	100	325

Notes: The Table presents summary statistics for the 3-month cross-currency basis with OIS rates (measured in percentage points) for currencies against USD. The cross-currency basis is adjusted for transaction costs as outlined in the text and is sampled daily. The "Direction" column indicates if the roundtrip goes from USD, swapped into Foreign Currency ("$USD \Rightarrow FCU$"), or to USD, swapped into USD ("$FCU \Rightarrow USD$"), at the spot leg of the swap. As FX quotes differ by the base currency, for AUD, EUR and GBP "$USD \Rightarrow FCU$" involves the bid side of the swap, while for others it involves the ask side. Positive numbers in the "Median" column implies that a roundtrip trade would have been profitable if OIS rates adequately captured the arbitrageurs' funding costs and the rate at which the swapped funds can be placed. "Std.dev" is standard deviation. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. We report results for two sample periods, "Post crisis" Jan 2013 – Apr 2016, and "MMF reform" Apr 2016 – June 2017.

Table OA.IV
Roundtrip cross-currency basis arbitrage with OIS rates. 1-week and 1-month maturity

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
	Direction	Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
						A. 1-month					
AUD	$FCU \Rightarrow USD$	4.1	12.5	65	49	847	-1.8	10.4	42	15	326
	$USD \Rightarrow FCU$	-8.9	11.5	20	6	846	-4.6	9.0	31	16	326
CAD	$FCU \Rightarrow USD$	-10.1	5.8	1	0	848	-20.7	11.5	0	0	326
	$USD \Rightarrow FCU$	3.7	5.8	81	45	847	13.7	11.2	98	73	326
CHF	$FCU \Rightarrow USD$	-30.1	33.6	0	0	848	-83.1	34.0	0	0	326
	$USD \Rightarrow FCU$	21.1	30.1	100	100	847	73.5	32.0	100	100	326
EUR	$FCU \Rightarrow USD$	-18.7	11.8	0	0	848	-58.4	27.5	0	0	326
	$USD \Rightarrow FCU$	14.6	11.3	95	87	847	53.7	26.7	100	100	326
GBP	$FCU \Rightarrow USD$	-9.4	6.7	0	0	848	-37.4	21.0	0	0	326
	$USD \Rightarrow FCU$	4.0	6.5	95	74	847	29.9	19.9	100	100	326
JPY	$FCU \Rightarrow USD$	-24.7	22.1	0	0	848	-72.2	43.2	0	0	326
	$USD \Rightarrow FCU$	19.1	21.0	100	100	847	60.0	42.5	100	94	326
						B. 1-week					
AUD	$FCU \Rightarrow USD$	-4.2	13.4	34	4	847	-9.1	13.8	18	0	326
	$USD \Rightarrow FCU$	-10.8	14.2	17	3	847	-10.1	11.9	13	0	326
CAD	$FCU \Rightarrow USD$	-12.3	8.4	4	0	848	-23.7	23.1	0	0	326
	$USD \Rightarrow FCU$	2.5	7.3	65	15	848	7.6	22.0	77	31	326
EUR	$FCU \Rightarrow USD$	-20.2	14.7	2	0	848	-44.9	64.2	0	0	326
	$USD \Rightarrow FCU$	11.1	11.8	94	72	848	32.2	55.7	100	100	326
GBP	$FCU \Rightarrow USD$	-10.6	13.5	0	0	848	-29.1	49.1	0	0	326
	$USD \Rightarrow FCU$	1.9	12.6	69	27	848	14.2	42.9	93	74	326
JPY	$FCU \Rightarrow USD$	-24.3	46.3	0	0	848	-54.9	78.6	0	0	326
	$USD \Rightarrow FCU$	12.0	32.4	98	81	848	23.5	63.7	92	46	325

Notes: The Table presents summary statistics for the 3-month and 1-week cross-currency basis with OIS rates (measured in percentage points) for currencies against USD. The cross-currency basis is adjusted for transaction costs as outlined in the text and is sampled daily. The "Direction" column indicates if the roundtrip goes from USD, swapped into Foreign Currency ("$USD \Rightarrow FCU$"), or to USD, swapped into USD ("$FCU \Rightarrow USD$"), in the spot leg of the swap. As FX quotes differ by the base currency, for AUD, EUR and GBP "$USD \Rightarrow FCU$" involves the bid side of the swap, while for others it involves the ask side. Positive numbers in the "Median" column implies that the median roundtrip trade would have been profitable if OIS rates adequately captured the arbitrageurs' funding costs and the rate at which the swapped funds can be placed. "Std.dev" is standard deviation. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. We report results for two sample periods, "Post crisis" Jan 2013 – Apr 2016, and "MMF reform" Apr 2016 – June 2017.

Table OA.V
Roundtrip cross-currency basis arbitrage with Interbank deposit rates. 3-month and 1-week maturity

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
				Deviation					Deviation		
	Direction	Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
						A. 3-month					
AUD	$FCU \Rightarrow USD$	-15.5	9.2	1	0	848	-41.3	19.7	0	0	326
	$USD \Rightarrow FCU$	-11.5	8.9	9	0	848	11.0	19.1	67	17	326
CAD	$FCU \Rightarrow USD$	-13.4	8.3	2	0	848	-41.8	21.6	2	0	326
	$USD \Rightarrow FCU$	-13.0	8.6	6	0	848	6.7	20.8	61	12	326
CHF	$FCU \Rightarrow USD$	-24.2	13.7	1	0	848	-60.6	18.7	0	0	326
	$USD \Rightarrow FCU$	-12.3	10.1	11	0	848	16.2	19.8	72	19	326
EUR	$FCU \Rightarrow USD$	-14.7	8.9	1	0	848	-43.6	18.4	0	0	326
	$USD \Rightarrow FCU$	-9.8	9.1	11	0	848	18.5	19.3	73	30	326
GBP	$FCU \Rightarrow USD$	-17.1	11.3	3	0	848	-43.9	17.6	0	0	326
	$USD \Rightarrow FCU$	-11.6	10.4	7	0	848	9.5	19.0	65	16	325
JPY	$FCU \Rightarrow USD$	-20.8	12.0	1	0	848	-48.4	19.7	0	0	326
	$USD \Rightarrow FCU$	-9.6	9.7	17	0	848	8.6	20.6	65	8	326
						B. 1-week					
AUD	$FCU \Rightarrow USD$	-18.0	15.6	1	0	848	-30.8	20.5	2	0	326
	$USD \Rightarrow FCU$	-15.9	13.9	3	0	848	-18.9	19.5	13	0	326
CAD	$FCU \Rightarrow USD$	-17.1	11.0	1	0	848	-42.0	27.5	0	0	326
	$USD \Rightarrow FCU$	-15.6	8.3	4	0	848	-5.3	26.4	35	0	326
CHF	$FCU \Rightarrow USD$	-24.2	35.8	0	0	848	-47.6	63.6	2	0	326
	$USD \Rightarrow FCU$	-14.8	26.8	5	0	848	-6.5	53.9	40	0	326
EUR	$FCU \Rightarrow USD$	-16.2	15.9	3	0	848	-43.5	63.8	0	0	326
	$USD \Rightarrow FCU$	-9.3	12.7	17	0	848	10.5	55.1	69	7	326
GBP	$FCU \Rightarrow USD$	-13.9	15.7	1	0	848	-38.7	51.6	0	0	326
	$USD \Rightarrow FCU$	-12.5	14.4	7	0	848	-1.0	43.3	49	4	326
JPY	$FCU \Rightarrow USD$	-21.7	39.6	1	0	848	-52.1	69.1	1	0	326
	$USD \Rightarrow FCU$	-9.0	26.8	17	0	848	0.4	59.1	50	0	325

Notes: The Table presents summary statistics for the 3-month and 1-week cross-currency basis with Interbank deposit rates (measured in basis points) for currencies against USD (1-month available on request). The cross-currency basis is adjusted for transaction costs as outlined in the text and is sampled daily. The "Direction" column indicates if the roundtrip goes from USD, swapped into Foreign Currency ("$USD \Rightarrow FCU$"), or to USD, swapped into USD ("$FCU \Rightarrow USD$"), in the spot leg of the swap. As FX quotes differ by the base currency, for AUD, EUR and GBP "$USD \Rightarrow FCU$" involves the bid side of the swap, while for others it involves the ask side. Positive numbers in the "Median" column implies that the median roundtrip trade would have been profitable if OIS rates adequately captured the arbitrageurs' funding costs and the rate at which the swapped funds can be placed. "Std.dev" is standard deviation. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. We report results for two sample periods, "Post crisis" Jan 2013 – Apr 2016, and "MMF reform" Apr 2016 – June 2017.

Table OA.VI
LOOP violations with money market rates. IBOR rates, 3-month maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\rightarrow\$}}_{\text{Swap-implied \$ rate}} \qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\rightarrow FCU}}_{\text{Swap-implied FCU rate}}$$

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
		Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
AUD	(i)	3.1	4.9	77	38	821	1.0	4.8	59	24	316
	(ii)	-4.9	4.9	12	0	821	-3.4	4.4	20	0	316
CAD	(i)	-19.9	6.2	0	0	800	-30.0	5.2	0	0	308
	(ii)	17.8	6.5	100	100	800	27.8	5.3	100	100	308
CHF	(i)	-16.4	17.6	0	0	821	-37.9	13.7	0	0	316
	(ii)	13.6	15.3	100	100	821	35.7	12.7	100	100	316
EUR	(i)	-15.2	9.3	1	0	818	-33.9	10.8	0	0	316
	(ii)	14.2	9.1	99	94	818	33.0	10.5	100	100	316
GBP	(i)	-2.3	4.2	10	2	821	-19.6	9.7	0	0	316
	(ii)	1.5	4.1	81	63	821	16.5	9.1	100	100	315
JPY	(i)	-17.0	14.0	0	0	821	-55.8	15.7	0	0	316
	(ii)	15.4	13.6	100	100	821	51.1	15.4	100	100	316

Notes: The Table presents descriptive statistics for 3-month LOOP deviations for IBOR and interbank deposit rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct \$ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a LOOP deviation exists, while (%M) measures the fraction of times a LOOP deviation can be observed over 22 consecutive trading days. Panel A shows calculations using IBOR rates, while Panel B is based on interbank deposit rates. We report results for two sample periods, "GFC and EUR crisis" Jan 2007 – Dec 2012, and "Post-crisis" Jan 2013 – Dec 10, 2015.

Table OA.VI
(Continued) LOOP violations with money market rates. IBOR rates, 1-week and 1-month maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\rightarrow\$}}_{\text{Swap-implied \$ rate}} \qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\rightarrow FCU}}_{\text{Swap-implied FCU rate}}$$

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
		Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
						A. 1-month					
AUD	(i)	0.87	7.69	53	28	821	-5.4	9.2	30	0	316
	(ii)	-3.4	7.8	37	13	821	0.9	8.1	54	23	316
CAD	(i)	-25.8	9.9	0	0	800	-50.9	10.1	0	0	308
	(ii)	22.2	10.2	100	100	800	46.1	9.8	100	100	308
CHF	(i)	-16.6	25.7	0	0	821	-48.7	32.8	0	0	316
	(ii)	12.7	22.4	100	98	821	43.0	30.5	100	100	316
EUR	(i)	-14.7	12.3	3	0	818	-47.3	25.7	0	0	316
	(ii)	12.8	11.9	95	87	818	45.5	25.0	100	100	316
GBP	(i)	-6.9	6.5	0	0	821	-33.2	20.7	0	0	316
	(ii)	5.3	6.5	96	87	821	28.6	19.4	100	100	316
JPY	(i)	-19.2	20.9	0	0	821	-61.2	36.6	0	0	316
	(ii)	16.4	20.0	100	100	821	52.1	34.5	100	100	316
						B. 1-week					
CAD	(i)	-6.8	8.4	15	0	821	-16.9	16.4	5	0	316
	(ii)	0.6	7.6	53	12	821	4.8	14.2	71	24	316
CHF	(i)	-16.4	35.6	0	0	821	-38.8	62.9	0	0	316
	(ii)	9.1	23.3	85	58	821	20.9	51.9	99	95	316
EUR	(i)	-15.2	11.8	4	0	818	-33.6	55.8	0	0	316
	(ii)	10.3	10.3	92	60	818	27.5	47.9	100	100	316
GBP	(i)	-9.2	10.1	0	0	821	-24.3	42.5	0	0	316
	(ii)	5.2	9.5	87	73	821	15.2	37.6	92	64	316
JPY	(i)	-18.3	39.8	0	0	821	-49.3	72.2	1	0	316
	(ii)	10.6	27.9	98	82	821	23.3	57.7	93	50	315

Notes: The Table presents descriptive statistics for 3-month LOOP deviations for IBOR and interbank deposit rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct $ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a LOOP deviation exists, while (%M) measures the fraction of times a LOOP deviation can be observed over 22 consecutive trading days. Panel A shows calculations using IBOR rates, while Panel B is based on interbank deposit rates. We report results for two sample periods, "GFC and EUR crisis" Jan 2007 – Dec 2012, and "Post-crisis" Jan 2013 – Dec 10, 2015.

Table OA.VI
(Continued) LOOP violations with money market rates. Interbank deposits, 1-month and 3-month maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} \;-\; \underbrace{y^{FCU\rightarrow\$}}_{\text{Swap-implied \$ rate}} \qquad\qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} \;-\; \underbrace{y^{\$\rightarrow FCU}}_{\text{Swap-implied FCU rate}}$$

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
				Deviation					Deviation		
		Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
						A. 3-month					
AUD	(i)	-5.0	9.2	18	0	848	-28.5	20.7	13	0	326
	(ii)	3.2	9.2	70	12	848	26.2	20.2	83	48	326
CAD	(i)	-3.0	8.4	29	0	848	-28.8	22.3	18	0	326
	(ii)	0.6	8.7	54	2	848	26.4	22.3	81	49	326
CHF	(i)	-13.0	13.8	8	0	848	-46.7	19.5	0	0	326
	(ii)	9.8	13.0	88	37	848	44.3	20.0	99	87	326
EUR	(i)	-3.6	9.0	22	0	848	-30.8	19.2	6	0	326
	(ii)	2.6	8.9	71	7	848	29.7	19.2	94	74	326
GBP	(i)	-4.9	11.6	34	0	848	-31.0	18.9	7	0	326
	(ii)	3.9	11.4	62	7	848	28.4	19.2	90	59	325
JPY	(i)	-9.0	11.6	12	0	848	-36.7	20.6	5	0	326
	(ii)	7.7	11.6	81	26	848	34.4	21.8	84	57	326
						B. 1-week					
AUD	(i)	-7.7	15.3	10	0	848	-18.8	19.8	7	0	326
	(ii)	-0.1	13.7	50	1	848	3.6	16.2	60	0	326
CAD	(i)	-6.7	10.7	11	0	848	-31.1	27.3	3	0	326
	(ii)	0.2	9.7	52	2	848	20.3	28.4	86	21	326
CHF	(i)	-13.7	35.8	2	0	848	-35.8	63.7	6	0	326
	(ii)	5.0	27.1	72	12	848	17.6	55.1	82	38	326
EUR	(i)	-5.8	15.5	14	0	848	-32.0	63.9	0	0	326
	(ii)	1.2	13.3	61	6	848	22.3	55.6	97	63	326
GBP	(i)	-3.6	15.4	23	0	848	-26.7	51.6	2	0	326
	(ii)	-0.4	14.6	48	0	848	15.4	45.4	88	20	326
JPY	(i)	-11.7	39.2	5	0	848	-41.0	69.1	1	0	326
	(ii)	3.4	26.2	68	1	848	20.3	57.9	82	22	325

Notes: The Table presents descriptive statistics for 3-month LOOP deviations for IBOR and interbank deposit rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct $ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a LOOP deviation exists, while (%M) measures the fraction of times a LOOP deviation can be observed over 22 consecutive trading days. Panel A shows calculations using IBOR rates, while Panel B is based on interbank deposit rates. We report results for two sample periods, "GFC and EUR crisis" Jan 2007 – Dec 2012, and "Post-crisis" Jan 2013 – Dec 10, 2015.

Table OA.VI
(Continued) LOOP violations money market rates. OIS rates, 1-month and 3-month maturity

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\to\$}}_{\text{Swap-implied \$ rate}} \qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\to FCU}}_{\text{Swap-implied FCU rate}}$$

		Post-crisis (2013 – Mar 2016)					MMF reform (Apr 2016 – Jun 2017)				
				Deviation					Deviation		
		Median	Std.	(%D)	(%M)	Obs	Median	Std.	(%D)	(%M)	Obs
						A. 3-month					
AUD	(i)	9.1	9.4	71	61	847	2.6	9.2	67	53	325
	(ii)	-11.0	9.7	23	10	847	-4.9	7.8	28	18	325
CAD	(i)	-6.9	4.5	1	0	848	-17.0	9.6	0	0	325
	(ii)	4.4	4.7	91	63	848	14.1	9.6	100	100	325
CHF	(i)	-33.0	26.9	0	0	848	-88.8	19.6	0	0	325
	(ii)	30.3	24.8	100	100	848	85.3	19.2	100	100	325
EUR	(i)	-18.2	10.6	0	0	846	-59.3	17.6	0	0	325
	(ii)	17.3	10.4	99	95	846	58.1	17.4	100	100	325
GBP	(i)	-7.1	4.7	0	0	847	-33.3	12.7	0	0	325
	(ii)	6.2	4.6	100	98	847	28.7	12.4	100	100	324
JPY	(i)	-24.2	16.9	0	0	848	-79.9	24.2	0	0	325
	(ii)	22.8	16.3	100	100	848	75.8	24.2	100	100	325
						B. 1-week					
AUD	(i)	-1.5	13.3	45	5	847	-5.9	13.2	25	0	326
	(ii)	-6.5	13.7	27	6	847	-8.1	12.6	21	0	326
CAD	(i)	-9.7	8.3	7	0	848	-19.9	23.0	1	0	326
	(ii)	3.7	7.4	71	27	848	8.6	22.0	82	37	326
EUR	(i)	-17.7	14.5	2	0	848	-40.9	64.2	0	0	326
	(ii)	13.2	12.1	95	75	848	34.6	55.9	100	100	326
GBP	(i)	-8.1	13.3	0	0	848	-25.6	49.1	0	0	326
	(ii)	4.2	12.7	83	61	848	16.2	43.0	95	75	326
JPY	(i)	-21.5	46.2	0	0	848	-51.8	78.5	0	0	326
	(ii)	13.9	32.4	99	87	848	25.1	63.7	92	57	325

Notes: The Table presents descriptive statistics for 3-month LOOP deviations for IBOR and interbank deposit rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct $ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a LOOP deviation exists, while (%M) measures the fraction of times a LOOP deviation can be observed over 22 consecutive trading days. Panel A shows calculations using IBOR rates, while Panel B is based on interbank deposit rates. We report results for two sample periods, "GFC and EUR crisis" Jan 2007 – Dec 2012, and "Post-crisis" Jan 2013 – Dec 10, 2015.

Table OA.VII
LOOP violations in commercial paper markets. 3-month maturity. Jan 2013-Jun 2017

$$(i) \quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\to\$}}_{\text{Swap-implied \$ rate}} \qquad\qquad (ii) \quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\to FCU}}_{\text{Swap-implied FCU rate}}$$

		Median	Std.	Deviation (%D)	(%M)	Obs
				A. 3-month		
High-rated banks (A-1/P-1)						
EUR	(i)	-11.6	11.9	6	0	1,098
	(ii)	10.6	11.6	92	79	1,098
GBP	(i)	-4.1	9.1	9	0	1,099
	(ii)	3.2	8.3	81	51	1,098
JPY	(i)	-3.1	3.9	20	0	1,096
	(ii)	1.1	4.2	59	32	1,096
Mid-rated banks (A-2/P-2)						
EUR	(i)	-7.2	10.1	6	0	1,099
	(ii)	6.1	9.8	90	63	1,099
GBP	(i)	-0.5	7.3	45	9	1,097
	(ii)	-0.4	6.6	47	19	1,096
JPY	(i)	-2.9	7.5	21	0	1,051
	(ii)	1.0	7.2	62	8	1,051

Notes: The Table presents descriptive statistics for 3-month LOOP deviations for commercial paper rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct $ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. Panel A shows calculations using commercial paper rates of the set of high-rated banks (A-1/P-1), while Panel B reports LOOP violations for mid-rated banks (A-2/P-2). The sample covers the post-crisis period (Jan 2013 – Jun 2017).

Table OA.VII
(Continued) LOOP violations in commercial paper markets. 1-month maturity. Jan 2013- Jun 2017

$$(i)\ \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\to\$}}_{\text{Swap-implied \$ rate}} \qquad (ii)\ \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\to FCU}}_{\text{Swap-implied FCU rate}}$$

		Median	Std.	Deviation (%D)	(%M)	Obs
				B. 1-month		
High-rated banks (A-1/P-1)						
EUR	(i)	-10.0	19.5	11	1	1,100
	(ii)	7.7	18.9	84	70	1,100
GBP	(i)	-3.4	14.2	8	0	1,100
	(ii)	1.6	13.3	69	37	1,100
JPY	(i)	-2.8	5.9	32	0	1,097
	(ii)	-1.6	7.9	42	21	1,097
Mid-rated banks (A-2/P-2)						
EUR	(i)	-7.3	17.7	8	0	1,096
	(ii)	5.4	17.1	85	52	1,096
GBP	(i)	-2.0	17.1	28	0	1,100
	(ii)	-0.1	16.0	50	25	1,100
JPY	(i)	-3.5	16.9	27	3	1,042
	(ii)	0.5	15.2	53	6	1,042

Notes: The Table presents descriptive statistics for 3-month LOOP deviations for commercial paper rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct $ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. Panel A shows calculations using commercial paper rates of the set of high-rated banks (A-1/P-1), while Panel B reports LOOP violations for mid-rated banks (A-2/P-2). The sample covers the post-crisis period (Jan 2013 – Jun 2017).

Table OA.VII
(Continued) LOOP violations in commercial paper markets. 1-week maturity. Jan 2013- Jun 2017

$$(i)\quad \underbrace{y^{\$}}_{\text{Direct \$ rate}} - \underbrace{y^{FCU\rightarrow\$}}_{\text{Swap-implied \$ rate}} \qquad (ii)\quad \underbrace{y^{FCU}}_{\text{Direct FCU rate}} - \underbrace{y^{\$\rightarrow FCU}}_{\text{Swap-implied FCU rate}}$$

		Median	Std.	Deviation (%D)	(%M)	Obs
				C. 1-week		
High-rated banks (A-1/P-1)						
EUR	(i)	-6.9	20.0	17	3	949
	(ii)	1.8	16.2	60	27	949
GBP	(i)	-2.8	11.7	19	1	912
	(ii)	-1.4	10.3	31	2	912
JPY	(i)	-1.8	51.1	33	0	895
	(ii)	-8.1	54.5	16	4	895
Mid-rated banks (A-2/P-2)						
EUR	(i)	-9.5	30.5	10	0	1,061
	(ii)	3.7	25.4	68	30	1,061
GBP	(i)	-4.1	21.3	23	0	1,087
	(ii)	-1.5	18.3	38	11	1,087
JPY	(i)	-4.8	8.4	25	0	365
	(ii)	-1.7	8.7	40	12	365

Notes: The Table presents descriptive statistics for 3-month LOOP deviations for commercial paper rates (measured in basis points) for currencies against USD. Both U.S. and foreign rates are measured at the ask (borrowing rates), consistent with a perspective of "borrower's arbitrage", while the swap is at the ask (bid) if the comparison is with direct \$ (FCU) rate. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists, while (%M) measures the fraction of times a roundtrip deviation can be observed over 22 consecutive trading days. Panel A shows calculations using commercial paper rates of the set of high-rated banks (A-1/P-1), while Panel B reports LOOP violations for mid-rated banks (A-2/P-2). The sample covers the post-crisis period (Jan 2013 – Jun 2017).

Table OA.VIII
Risk-free CIP arbitrage funded via the CP market and invested in central bank deposits. 1-month and 1-week maturity

	1-month					1-week				
			Deviation					Deviation		
	Median	Std.	(%D)	(%M)	Obs.	Median	Std.	(%D)	(%M)	Obs.
I: Post-crisis to beginning MMF reform period (Jan 2013 – Mar 2016)										
A. Mid-rated banks (A-2/P-2)										
AUD	**-42.3**	10.1	0	0	702	**-38.8**	11.7	0	0	698
CAD	**-7.2**	7.3	16	3	784	**-3.4**	7.4	31	1	778
CHF	**8.9**	24.3	98	82	784	**7.2**	21.9	82	50	778
EUR	**-9.1**	14.6	19	16	781	**-5.1**	11.9	26	5	775
GBP	**0.2**	7.5	51	22	783	**3.4**	9.3	72	40	777
JPY	**13.0**	20.8	95	82	782	**9.2**	27.5	94	62	776
B. High-rated banks (A-1/P-1)										
AUD	**-34.6**	8.7	0	0	702	**-31.7**	10.0	0	0	694
CAD	**1.3**	6.9	59	26	784	**3.2**	8.1	68	26	776
CHF	**16.6**	24.8	100	97	784	**13.2**	23.6	94	75	776
EUR	**1.3**	15.3	52	46	781	**0.8**	13.5	53	37	773
GBP	**8.7**	6.0	100	100	783	**10.9**	10.5	92	83	775
JPY	**20.2**	21.3	100	100	782	**16.3**	29.6	100	95	774

Notes: The Table shows CIP deviations, measured in basis points, for an implementable strategy involving borrowing in the U.S. market. The sample covers the post-crisis period prior to the adjustment phase of the U.S. money market fund (MMF) reform (January 2013–March 2016). Positive numbers represent arbitrage profits. The Commercial Paper (CP) funding rate differs according to two rating categories, either high-rated banks (A-1/P-1) or mid-rated banks (A-2/P-2). The crucial aspect for a proper arbitrage, seen from the arbitrageur's perspective, is that the investment is risk-free, here represented by investing in central bank deposits. Columns give the median CIP arbitrage profit, the standard deviation of CIP arbitrage profits, and proportion of days (%D) and months (%M) during the sample when a positive arbitrage profit is observed.

Table OA.VIII
(Continued) CIP arbitrage funded via the CP market and invested in central bank deposits. 1-month and 1-week maturity

	1-month					1-week				
			Deviation					Deviation		
	Median	Std.	(%D)	(%M)	Obs.	Median	Std.	(%D)	(%M)	Obs.
II: MMF reform sample (Apr 2016 – June 2017)										
A. Mid-rated banks (A-2/P-2)										
AUD	**-45.3**	10.4	0	0	294	**-45.2**	17.7	0	0	293
CAD	**-3.4**	10.8	38	0	316	**-4.6**	18.9	36	0	314
CHF	**36.0**	29.0	100	100	316	**16.7**	46.6	97	71	314
EUR	**30.3**	23.0	100	94	316	**14.9**	42.0	99	80	314
GBP	**16.5**	17.9	96	69	316	**7.1**	31.4	83	34	314
JPY	**34.1**	34.1	100	93	307	**7.5**	50.5	70	12	305
B. High-rated banks (A-1/P-1)										
AUD	**-32.4**	7.6	0	0	294	**-31.0**	11.3	1	0	254
CAD	**6.7**	9.7	88	50	316	**9.6**	15.2	81	38	276
CHF	**48.5**	31.7	100	100	316	**30.2**	55.5	100	100	276
EUR	**43.3**	25.2	100	100	316	**28.8**	50.3	100	100	276
GBP	**28.8**	19.5	100	100	316	**19.4**	39.7	98	80	276
JPY	**47.0**	36.5	100	100	307	**23.0**	60.8	88	37	267

Notes: The Table shows CIP deviations, measured in basis points, for an implementable strategy involving borrowing in the U.S. market. The sample covers the post-crisis period prior to the adjustment phase of the U.S. money market fund (MMF) reform (January 2013–March 2016). Positive numbers represent arbitrage profits. The Commercial Paper (CP) funding rate differs according to two rating categories, either high-rated banks (A-1/P-1) or mid-rated banks (A-2/P-2). The crucial aspect for a proper arbitrage, seen from the arbitrageur's perspective, is that the investment is risk-free, here represented by investing in central bank deposits. Columns give the median CIP arbitrage profit, the standard deviation of CIP arbitrage profits, and proportion of days (%D) and months (%M) during the sample when a positive arbitrage profit is observed.

Table OA.IX
CIP arbitrage and FX swap market order flow imbalances across maturities (invest in CB deposit). Sample: Apr 2016-Jun 2017.

	3-month		1-month		1-week	
	A-2/P-2	A-1/P-1	A-2/P-2	A-1/P-1	A-2/P-2	A-1/P-1
	(1)	(2)	(3)	(4)	(5)	(6)
Constant	-0.936	0.159	0.475	0.371	1.228	1.953
	(-2.02)	(0.77)	(0.90)	(0.74)	(1.13)	(1.38)
Lagged level	-0.100	-0.020	-0.033	-0.015	-0.095	-0.037
	(-2.80)	(-1.41)	(-1.27)	(-1.20)	(-2.06)	(-0.52)
Swap OF, in arb.	0.374	0.531	1.239	1.280	3.479	3.129
	(1.65)	(4.81)	(4.49)	(5.40)	(3.22)	(2.62)
Swap OF, no arb.	0.330	0.319	0.180	0.438	0.441	1.153
	(2.35)	(2.38)	(0.65)	(1.64)	(0.99)	(1.53)
Dollar index, in arb.	0.001	0.005	0.004	0.017	0.057	0.059
	(0.06)	(0.87)	(0.16)	(1.54)	(1.62)	(1.73)
Dollar index, no arb.	-0.002	0.005	-0.024	0.008	0.007	0.003
	(-0.20)	(0.85)	(-1.46)	(0.86)	(0.48)	(0.16)
Lagged dependent	-0.163	-0.048	-0.196	-0.009	0.025	0.045
	(-1.49)	(-1.34)	(-3.39)	(-0.17)	(0.42)	(0.68)
Obs.	924	924	924	924	907	702
adj.R^2	0.08	0.04	0.08	0.02	0.02	0.01

Notes: The Table shows results from panel-regressions for changes in CIP deviations, measured in basis points, across six different currencies. CIP deviations are based on funding in the U.S. CP market for banks with either A-2/P-2 rating or high-rated banks with A-1/P-1-rating, and invested in central bank deposits (Panel A) or Treasury bills (Panel B). The constant (not reported) and error-correction term (lagged level of CIP deviation) have constant coefficients across deviation regimes, while the other explanatory variables are allowed to have different effects, depending on whether a deviation exists. The return on FX spot, and the liquidity premia differential, are measured in basis points, while swap order flows are standardized by own standard deviation. Robust t-statistics (cross-sectional clustering) are reported in parenthesis below coefficient estimates. Sample: April 2016 – June 2017.

Table OA.X
Quantitative Easing (QE) and End-of-Quarter effects

	CHF	EUR	JPY	Panel
EoQ during QE	0.343	0.862	0.635	0.526
	(3.27)	(3.90)	(3.85)	(5.62)
EoQ pre-QE	-0.022	0.006	0.014	0.003
	(-0.54)	(0.19)	(0.55)	(0.24)
Obs.	2,192	2,186	2,192	6,570
adj.R^2	0.05	0.16	0.12	0.09

Notes: Regression of 1-week IBOR LOOP violations on dummy for End-of-Quarter-period, interacted with dummy for before and after implementation of Quantitative Easing (QE). Constants and fixed effects supressed. Sample: January 2009 – June 2017.