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Segmented Money Markets and Covered Interest Parity Arbitrage*

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Segmented Money Markets and Covered Interest Parity Arbitrage

Abstract

This paper studies the violation of the most basic no-arbitrage condition in international finance – Covered Interest Parity (CIP). To understand the CIP conundrum, it is key to (i) account for funding frictions in U.S. dollar money markets, and (ii) to study the challenges of swap intermediaries when funding liquidity evolves differently across major currency areas. We find that CIP holds remarkably well for most potential arbitrageurs when applying their marginal funding rates. With severe funding liquidity differences, however, it becomes impossible for dealers to quote prices such that CIP holds across the full rate spectrum. A narrow set of global top-tier banks enjoys risk-less arbitrage opportunities as dealers set quotes to avert order flow imbalances. We show how a situation with persistent arbitrage profits arises as an equilibrium outcome due to the constellation of market segmentation, the abundance of excess reserves and their remuneration in central banks' deposit facilities.

JEL Classification: E43, F31, G15.

Keywords: Covered Interest Parity; Money Market Segmentation; Funding Liquidity Premia; FX Swap Market; U.S. Dollar Funding

Recent reports suggest that Covered Interest Parity (CIP) — once regarded as the most robust regularity in international finance — no longer holds.[1] CIP postulates that it is impossible to earn a profit by borrowing in one currency and lend in another, while fully covering the foreign exchange (FX) risk.[2] In more concrete terms, this is expressed as:

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

where $r_{\$}$ and $r_{\star}$ denote U.S. and foreign interest rates with same maturity, S is the spot exchange rate expressed in units of U.S. dollars (USD) per unit of foreign currency and F is the forward rate of maturity equal to that of the interest-bearing assets. If all transactions are closed simultaneously and counterparty risks are zero (in particular for the lending leg), CIP boils down to a no-arbitrage condition. Based on carefully constructed transaction-level data before the Great Financial Crisis (GFC), Akram, Rime, and Sarno (2008) found that any CIP deviations (after accounting for transaction costs) were too small and short-lived to give rise to economically significant arbitrage profits.

Since the onset of the GFC, however, seemingly large deviations from CIP have emerged, even in some of the world's most liquid currencies. The breakdown of no-arbitrage during the heights of the GFC and the European sovereign debt crisis — periods which saw price dislocations across many asset classes — may not be surprising. However, Du, Tepper, and Verdelhan (2016), Borio, McCauley, McGuire, and Sushko (2016), and Avdjiev, Du, Koch, and Shin (2016) suggest that the anomaly has been particularly severe during the much calmer period since mid-2014. This stands in stark contrast to the above-mentioned pre-crisis evidence, and has puzzled academics, central bankers and market participants alike.

To make progress in the understanding of the CIP puzzle, we focus on three distinct aspects: *First*, we provide an in-depth analysis of the profits from risk-less arbitrage strategies that are implementable by the main players in international money markets, paying close attention to the *marginal funding costs* of the typical arbitrageurs.[3] *Second*, we account for the substantial segment-

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

[2] Keynes (1923) is credited with coining the term, yet empirical research on the topic only emerged in the mid-1970s, following the collapse of the Bretton Woods regime. Prominent early papers testing the CIP condition notably include inter alia Frenkel and Levich (1975, 1977).

[3] To implement a realistic arbitrage position, one needs tradeable prices sampled at approximately the same time to avoid execution risk (see, e.g. Kozhan and Tham, 2012). A high-quality, high-frequency, transaction-level dataset is therefore key in assessing a no-arbitrage relation like CIP.

ation in international money markets in the post-GFC environment. This has been manifesting itself (among other things) in a large dispersion of short-term interest rates, especially in U.S. dollar markets (Duffie and Krishnamurthy, 2016). At the same time, effective funding costs and liquidity premia have compressed in other key currency areas, mainly due to the abundance of central bank reserve balances created as a by-product of Quantitative Easing. It thus has become impossible for the no-arbitrage condition to hold for all different money market rates at the same time. *Third*, we study the challenges faced by key intermediaries against the backdrop of substantial imbalances in the demand and supply of U.S. dollars in the swap market. To our knowledge, this is the first paper investigating the role of order flow on price fluctuations in the FX swap market.

Studying the economic mechanisms that have possibly altered one of the most fundamental no-arbitrage conditions in finance is crucial. It provides a unique opportunity to better understand the state of the global financial system and the key constraints faced by the market participants that operate in it. The key market that links money markets in different currencies, and is used for CIP arbitrage, is the FX swap market. An FX swap is an OTC derivative which can be thought of as a spot transaction coupled with an opposite forward contract.[4] By any standards, the FX swap market is huge with a daily trading volume exceeding USD 2 trillion (BIS, 2016). If the functioning of this crucial market is impaired, the relative prices of assets and debt across currencies will be significantly distorted. In turn, this may affect monetary policy transmission, the currency composition of financial and non-financial companies' balance sheets and government borrowing costs. Given their possible impact on aggregate outcomes, the funding and intermediation frictions underlying CIP dislocations that we study in this paper should thus be of relevance from a broader macro-theory perspective as well.

We focus on short-term (three-month) arbitrage opportunities for global banks that we consider to be the critical CIP arbitrageurs in the money market segment. They are present in funding markets in multiple currencies, face constant funding/liquidity needs and can flexibly choose the cost-optimal funding option. Other important market participants, e.g. hedge funds, are less likely to engage as major arbitrageurs. This is because banks generally avoid charging their customers below their own funding cost and hence would be reluctant to provide hedge funds with the leverage

[4]FX swaps are the primary vehicle through which sophisticated players implement CIP arbitrage. They are widely used by market participants to facilitate cross-border borrowing and investment, and manage exposure to FX risk. Trading volume in FX swaps exceeds that in outright forwards by a significant margin (BIS, 2016).

to profitably exploit any deviations.[5]

We distinguish between violations of Covered Interest Parity (CIP) and the Law-of-One-Price (LOOP). LOOP violations give rise to an incentive to take advantage of cross-country differences in borrowing rates, but they do not necessarily imply (self-financed) arbitrage opportunities. CIP deviations, by contrast, are associated with *risk-less* profits from a self-financing *roundtrip* arbitrage strategy. Such trades require that the arbitrageur be able to place funds in a risk-free investment vehicle after swapping. Most of this paper focuses on understanding violations of the CIP condition, but, as we show, it is important to look at both relationships jointly for different types of banks to understand equilibrium outcomes in the FX swap market.

Our approach reveals three key lessons about the functioning of international money and FX swap markets. *First*, we show that, in fact, the law of one price holds quite well when we pick money market rates that reflect banks' marginal funding costs. LOOP deviations are negligible for interbank deposit rates and Commercial Paper (CP) rates – in stark contrast to interbank offer (IBOR) rates, Overnight-Index-Swap (OIS) or General Collateral (GC) repo rates.[6] Drawing on a panel of interbank deposit rates across currencies allows us to extract proxies for *funding liquidity premia*. We show that LOOP/CIP deviations based on OIS rates tend to co-move strongly with measures of funding liquidity premium differentials across countries. This finding suggests that these measures of deviations – while signalling potential trading profits – may not be considered as purely *risk-less* from the arbitrageurs' perspective. Instead, they signal an opportunity to enhance returns at the expense of taking additional funding liquidity risk on the balance sheet.

Second, we find that *risk-free* CIP arbitrage opportunities do indeed exist – but only for a confined set of highly-rated global banks. We obtain this result by investigating the pricing in major unsecured funding markets such as commercial paper (CP).[7] However, the CP market in

[5]To arbitrage price dislocations, hedge funds are dependent on bank/prime broker funding (see, e.g., Moore, Schrimpf, and Sushko, 2016). In contrast to leveraged investors like hedge funds, traditional 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 swaps market, such opportunistic behavior cannot be regarded as arbitrage in the strict sense as it does not involve a full (self-financing) roundtrip. Moreover, asset managers face restrictions by their mandates, and while these may in principle evolve, any change tends to happen quite slowly. The same applies with respect to the behavior of large non-financial corporations.

[6]A main reason 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 Appendix C.

[7]It is well known that in the aftermath of the GFC, activity in unsecured interbank markets has dropped significantly, especially for maturities beyond one week. This implies that this market segment is no longer available as a marginal source of (term) funding for banks. Instead, banks' marginal short-term wholesale funding stems from unsecured non-bank funding sources, such as commercial paper or certificates of deposit.

U.S. dollars is fragmented, with large dispersion in funding costs across banks. The vast majority of banks around the globe faces prohibitively high marginal funding costs in U.S. dollars. But, for top-tier banks with access to U.S. CP funding on favorable terms and with access to the deposit facilities of foreign central banks (i.e. a risk-free investment vehicle), arbitrage is economically viable. Such arbitrage opportunities are much less attractive if short-term government paper is considered as the risk-free investment asset. The reason is that market rates on government securities react to movements in the term funding liquidity premium in the respective currency. Moreover, all market participants have access to government securities, not only eligible counterparties of the central bank. On the other hand, the remuneration on reserves in central banks' deposit facilities is insensitive to volume.

Finally, we show that the existence of persistent risk-less arbitrage profits for a confined set of players can indeed be part of an equilibrium outcome in a world of segmented money markets and abundance of central bank liquidity. We arrive at this conclusion by studying the challenge faced by a market maker, which quotes FX swap prices to extract intermediation markups, but which has a strong incentive to balance customer order flow.[8] The post-GFC constellation of increased heterogeneity in U.S. dollar funding costs, and a compression of liquidity premia in other major currency areas on the back of Quantitative Easing, has rendered it impossible for a single price in the FX swap market to be consistent with the law of one price for all rates in money markets simultaneously.

In such a situation, an FX swap market maker aiming to maintain a balanced order flow (and hence inventory), must carefully set quotes in order to incentivize flows in opposite directions from different market participants. We show that, to face a balanced flow, a market maker needs to quote FX swap prices to provide top-tier banks with an incentive to swap out of the U.S. dollar into foreign currency. This flow is used to accommodate demand pressures by the bulk of lower-tier banks facing prohibitively high direct U.S. dollar funding cost. Their compressed borrowing costs in domestic currencies due to the abundance of central bank reserve balances renders it attractive to turn to FX swaps to raise U.S. dollars.

It is important to highlight that flows in both directions are bounded. Top-tier global banks

[8] 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.

(with an incentive to supply U.S. dollars via swaps) face significant limitations in scaling their U.S. dollar borrowing for the purpose of CIP arbitrage. First and foremost, the main marginal providers of unsecured dollar funding, U.S. money market funds, typically apply strict concentration limits with regard to their counterparties.[9] Moreover, banks in the lower-tier segment facing opposite incentives (that is, raising U.S. dollars via swaps) represent a fairly large market share, suggesting that imbalances can grow significantly.[10] Finally, banks potentially engaging in the arbitrage face regulatory constraints as well as internal limits with regard to balance sheet allocation.[11] While risk budgets can change, these considerations suggest that the amount of capital that could possibly be deployed to CIP arbitrage is relatively small and slow-moving (e.g. Duffie, 2010).

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 swaps market to obtain USD funding. Faced with such imbalances (which tend to coincide with broader funding constraints in the U.S. dollar), swap market makers revise their quotes to attract matching opposite flow. As a consequence, a set of market players may enjoy arbitrage opportunities.

Our findings suggest a new perspective on CIP that takes into account the large degree of money market segmentation that has emerged in the post-GFC world. Banks face highly heterogeneous funding costs and money market rates reflect liquidity premia to a much greater extent than before the crisis. Taking these features into account, we show that the pricing in money and FX swap markets has settled on a new equilibrium. This equilibrium is still largely consistent with the original paradigm of CIP: arbitrage profits – after accounting for trading costs and risk – are very difficult to reap for most players. Yet, such profits can be part of an equilibrium outcome and persist for prolonged periods. All in all, this suggests that common measures of CIP deviations will likely continue to reflect money market segmentation and differences in liquidity premia across currencies rather than provide an indication of a "free lunch".

[9] From October 14 2016, U.S. money market funds investing in securities issued by banks (prime funds) have been subject to new and stricter regulations (floating Net Asset Values (NAVs), liquidity fees and redemption gates). This has reduced U.S. prime funds' assets under management substantially.

[10] The flows by lower-tier banks react to lower funding rates (obtained indirectly via the swap market), and hence cannot be seen as self-financed arbitrage trades. Hence, they are limited to those banks with actual borrowing needs. This also highlights that the marginal funding costs of lower-tier global banks are an important ingredient in determining how prices adjust in the FX swap market.

[11] For a further discussion of the impact of regulation, see Section IV.

Related literature. The GFC has, un-surprisingly, revitalized research interest in the validity of the CIP condition. A first wave of papers focused on the U.S. dollar funding shortages of global banks as key driver of the relationship's breakdown. Important contributions include Baba, Packer, and Nagano (2008), Baba and Packer (2009), 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). Based on this research, a consensus emerged that provision of U.S. dollar liquidity via major central banks' swap lines with the Federal Reserve was instrumental in alleviating the dollar shortage and helped to ease the CIP pricing dislocation significantly.

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 (2016) carefully document the price dislocations and show that measures of the cross-currency basis tend to be correlated with nominal interest rate differentials in the cross-section of currencies. They argue that the pricing anomaly stems from global demand and supply imbalances arising from differences in countries' net international positions and that deviations are too large to be explained by transaction costs alone, giving rise to significant arbitrage opportunities. Sushko, Borio, McCauley, and McGuire (2016) further corroborate the role of imbalances in the FX swap market. Drawing on measures of dollar funding gaps of different banking systems, they highlight the role of FX hedging demand as an important driver.[12] Iida, Kimura, and Sudo (2016) focus on the impact of monetary policy divergence and counterparty risk, extending the model of Ivashina, Scharfstein, and Stein (2015). Wong, Leung, and Ng (2016) take a different approach, claiming that the traditional version of CIP has to be adjusted for the counterparty risk embedded in domestic and foreign money market rates.[13] In relation to this evolving literature, a distinct feature of our work is to link CIP-related pricing distortions to (i) the role of funding frictions arising from segmentation in U.S. dollar markets, and (ii) intermediation frictions arising from the challenges of swap intermediaries in balancing order flow.

Last, but not least, our work relates more broadly to work emphasizing the role of intermediation

[12] Cenedese, Della Corte, and Wang (2017) 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.

[13] 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 LOOP deviations cannot be seen as an arbitrage opportunity.

frictions and the role of limits to arbitrage.[14] Gabaix and Maggiori (2015) provide an equilibrium model where intermediation frictions can lead to the failure of both uncovered and covered interest parity. Depending on the parameter constellation, segmentation effects similar to the ones highlighted in our paper can arise. 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). And, it relates to the literature that looks specifically at the effects of segmentation in money markets (e.g. Bech and Klee, 2011; Duffie and Krishnamurthy, 2016).

Roadmap. The rest of the paper is structured as follows. Section I lays out the main concepts and the data requirements. Section II highlights the need to account for the evolution of funding liquidity premia across different currencies when studying LOOP and CIP deviations. Section III investigates LOOP violations and CIP arbitrage in international money 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 extent of risk-less arbitrage involving the remuneration of reserves on behalf of central banks. Section IV 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. Section V concludes. A separate Online Appendix contains supplementary material.

I. CIP arbitrage: concepts and data

This section starts by: (i) providing definitions of key terms; (ii) lays out the main arguments behind the choice of money markets rates; (iii) further motivates that accounting for segmentation is of key importance in testing the validity of no-arbitrage relationships in international money markets; and (iv) provides an overview of our dataset.

[14]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.

A. *LOOP vs CIP*

We distinguish closely between two main concepts in international money markets – the Law of One Price (LOOP) and Covered Interest Parity (CIP). Our main focus is on CIP, but we also frequently refer to LOOP as well. It is thus useful to clarify the terminology from the outset.

LOOP compares the *direct* borrowing costs in currency B with the *implied* borrowing cost based on currency A swapped into currency B.[15] It is important to stress that LOOP does not fulfil the criteria of a no-arbitrage condition. It merely implies that borrowing costs in similar funding vehicles should be equal across currencies. A violation of LOOP may, however, attract more borrowers to the cheap currency, leading to a gradual equalization of borrowing costs.

CIP is based on the basic proposition that a *self-financed* arbitrage trade – borrowing currency A, using an FX swap in order to convert the proceeds and investing in a risk-free asset in currency B – should note yield any profits. To exploit CIP deviations, the arbitrageur has to perform a full *round-trip*, i.e. he needs to be able to borrow capital in one currency and invest risk-free in another.

Example. CIP arbitrage strategies can be implemented in many different ways. An example of the sequence of trades involved is provided for illustration below:

1. Borrow U.S. dollar for, say, 30 days, at rate $r_{t;\$}$
2. Buy euros spot to obtain $1/S$ euros, and simultaneously enter a forward contract F reversing the currency exchange at a predetermined price in 30 days,
3. Invest the euro-denominated funds at the currently available 30-day euro rate $r_{t;\star}$.

A requirement is that all transactions (borrowing, spot, forward and lending) are made simultaneously and hence the profits are known ex-ante. 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-financing) arbitrage trade. The no-arbitrage condition then defines the relation commonly known as CIP. In the real world, 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).

[15] Or alternatively the investment return in currency B with the implied investment return based on currency A swapped into currency B.

It is also quite common to refer to the cross-currency basis, which we define as follows:

$$Basis_t = \frac{F_t}{S_t}(1 + r_{t;\star}) - (1 + r_{t;\$}), \tag{1}$$

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 $(1 + r_\$)$.

Transaction costs. Any investigation of the possible failure of CIP needs to carefully account for the fundamental requirements for a self-financing arbitrage: (i) all legs of the trade need to be adequately adjusted for their costs; (ii) the instruments involved need to be tradeable; and (iii) the sequence of trades involved needs to be free of risk for the arbitrageur. Related to point (i), an important component of the costs comes from bid-ask spreads. In the example above, the arbitrageur will be borrowing at ask rates, lending at bid rates, buying spot at ask (euro is the base currency in dollar-euro exchange in the example above), and selling forward at the bid.

Taking bid/ask spreads into account, and both from the perspective of U.S. and foreign borrowing, CIP arbitrage is *not* profitable under the following conditions:

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

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

where the superscripts a and b symbolize ask and bid rates, respectively, and $r^a > r^b$.[16] Equation (1) implies that the borrowing rate (ask) in U.S. dollars has to be equal or higher than the implied lending rate (bid) measured in U.S. dollars for the no-arbitrage condition to hold. Similarly, Equation (2) implies that the borrowing rate (ask) in the foreign currency has to be equal or higher than the implied lending rate (bid) measured in foreign currency for the no-arbitrage condition to hold.[17] It can be shown that a possible arbitrage opportunity in one direction does not necessarily imply a profitable one in the reverse direction.

[16] See Appendix A and the Online Appendix for further details on calculating deviations from CIP while respecting all market conventions.

[17] 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).

B. *Which money market rates?*

A key point of this paper is that careful attention needs to be paid in order to pick the appropriate interest rates when investigating the LOOP/CIP condition. In reality, there is (unlike in the textbook case) not a single interest rate for a given maturity and currency, but a plethora of rates. In this subsection, we lay out the main considerations guiding the choice of rates in our subsequent analysis.

Funding side. When studying LOOP violations and CIP arbitrage, it is important to rely on rates that most adequately capture the marginal funding costs of the critical arbitrageurs in international money markets. We start our investigation with interbank borrowing rates and consider both interbank offered rates (IBOR) and deposit rates which have traditionally been used for LOOP and CIP calculations.[18]

However, it is well-known, that the unsecured interbank market, once regarded as a trustworthy source for banks' marginal funding costs, is no longer a vibrant source of term funding for banks.[19] To investigate banks' marginal funding costs in the current environment, it is therefore paramount to investigate non-bank money market instruments. This includes, for instance, Commercial Paper (CP) or Certificates of Deposit (CD). Such instruments can be issued with great flexibility and represent unsecured claims on banks, typically held by non-banks, such as money market funds or cash-rich corporations.

Banks' borrowing costs from the non-bank sector generally tend to be lower than those on interbank borrowing. This is because banks have to incorporate balance sheet costs into their quotes of unsecured interbank rates. For a typical bank, net interest margins are the main component of profitability and hence the funding rate from non-banks can be seen as the primary cost component. To generate the return on equity required by its shareholders, the bank's lending rate has to reflect the additional capital and the associated return required on this capital. And, it has to take into

[18] Note that interest rates on Overnight-Index-Swaps (OIS) contracts, while close to risk-free, do not account for term funding liquidity premia and, thus, do not represent the marginal funding costs of the typical arbitrageurs in international money markets. The same applies to General Collateral (GC) repo rates. We provide a more detailed analysis of CIP arbitrage strategies involving OIS contracts in Section II.

[19] See e.g. Figure A.1 in the Online Appendix which shows the substantial decline in interbank loans in the post-GFC environment based on U.S. data. Similar trends can be observed in other currency areas, see e.g. the ECB's money market survey (ECB, 2015).

account any additional regulation that may impact the return on equity. This means that unsecured interbank rates that banks quote to each other are likely to reflect these costs. By contrast, funding costs from the non-bank sector (such as CP or CD rates) do not reflect a cost for expanding the balance sheet. These interest rates are thus perfectly suitable when assessing banks' potential risk-free arbitrage opportunities (i.e. trades which do not consume capital). Non-bank wholesale rates are also suitable for studying LOOP for borrowers as CP and CD-rates reflect banks' true funding costs. Our empirical analysis thus focuses on non-bank wholesale funding rates.

Investment side. A key requirement for the study of CIP arbitrage opportunities is to make sure that the funds (once swapped into a different currency) can be placed into a truly risk-free investment asset. Interbank deposits do not fulfil that criterion due to credit risk. Thus, we turn instead to government T-Bill rates and central banks (CB) deposit facilities.[20] The main difference between the T-Bill and the CB deposit rate is that the former is widely accessible by all market participants, whereas the latter is only available to eligible counterparties with criteria determined by the central bank. We do this because the more favorable rates only apply to a restricted cash amount.[21]

C. Segmented markets: an illustration

The post-crisis environment of segmentation and fragmentation in international money markets has manifested itself in an increased degree of heterogeneity in banks' funding costs. These developments have been particularly pronounced in the case of the U.S. dollar due to its status of a primary global funding currency. At the same time, liquidity premia have evolved differently across currencies, partly as a result of the excess liquidity resulting from unconventional policies. A key implication of market segmentation is that it has become impossible for the law of one price in international money markets to hold for all different rates, unless risk spreads and liquidity premia evolve symmetrically across currencies.

[20]In cases where the central bank has adopted a tiered deposit remuneration schedule, we use the lowest rate as an expression of the marginal rate of remuneration (Bech and Malkhozov, 2016). Moreover, the CB deposit rate is in most cases unresponsive to the amount of reserves placed in the facility.

[21]Note, however, that even the CB deposit facility cannot be regarded as fully risk-free as the central bank may unexpectedly lower the remuneration of excess reserves during the term of the arbitrage trade. Given that the magnitude of this risk is fairly small, at least in most cases, we neglect it for now.

[Insert Figure 1 about here]

Figure 1 depicts how these mechanisms have affected U.S. dollar money market rates post-crisis. Panel (a) shows the difference in banks' USD funding costs in the CP market, depending on the credit rating of the bank. Even at a three-month maturity, the difference between a top-rated bank (A-1+/P-1) and a lower-rated bank (A-2/P-2) is about 20 basis points. The funding cost differential across different currencies is summarized in Panel (b), based on LIBOR-OIS spreads. While LIBOR is a highly imperfect measure of banks' funding costs (e.g. Duffie and Stein, 2015), it nevertheless provides an indication of how term funding liquidity premia evolve across currencies. As can be gleaned from the Figure, 3-month LIBOR-OIS spreads have been significantly larger in the U.S. dollar than in other major currencies. The substantial difference between funding rates in USD and those in other major countries are confirmed in Panels (c) and (d) using 3-month CP-OIS spreads for top-rated and lower-rated banks.

This suggests that obtaining term liquidity (even for those banks with direct access to USD markets) has been much more expensive in the U.S. dollar than obtaining funding over the same horizon in other currencies. Moreover, the heterogeneity in funding costs across banks has remained elevated ever since the onset of the GFC. This can be inferred from the range of banks' submission to the USD LIBOR panel, shown in Figure A.2 in the Online Appendix.[22]

D. Data

The construction of our dataset closely follows the principles for CIP arbitrage. Table 1 gives an overview of the data and their sources. It also indicates how well a certain variable scores with regard to the principles required for a risk-less arbitrage, as laid out above.

[Insert Table 1 about here]

We follow Akram, Rime, and Sarno (2008) and assemble a high-quality, high-frequency data set from Reuters on FX spot and swap rates. High-frequency data are timed to the thousand of second, and are from 2005 until December 2015.[23] Our study comprises the set of most liquid currencies

[22] Further evidence on this is provided below (using issuance data on Certificates of Deposits (CD)).

[23] All prices are matched to the exact time. If a price is not available, we fill in with previous prices. Only weekdays between GMT 01:00-18:00, on active trading days, are considered.

worldwide, that is, those of Australia (AUD), Canada (CAD), the euro area (EUR), Great Britain (GBP), Japan (JPY), Switzerland (CHF), all quoted against the U.S. dollar (USD).

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. We use FX swaps instead of forwards as it is usually via swaps that sophisticated participants in interbank markets implement forward transactions. For FX swaps, we rely on two different sources, indicative quotes and data from an electronic limit order book. The indicative quotes are our preferred source since they are quoted for all maturities and updated more frequently.[24]

[Insert Table 2 about here]

Finally, we create a measure of daily FX swap order flow, drawing on swap transactions from the Reuters D2000-2 platform. The latter 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. Our order flow metrics are constructed to measure the net number of buyer/seller-initiated trades with U.S. dollars at 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.

As discussed above, our analysis relies on various types of money market rates. Based on data from Reuters, we assemble high-frequency data for ask and bid quotes of interbank deposit rates, as in Akram, Rime, and Sarno (2008). The deposit quote on the ask side is an indication of the rate 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 continously throughout the day.

In the same vein, we retrieve bid and ask quotes of Overnight-Indexed-Swap (OIS) rates for our set of currencies (also from Reuters). Interbank Offer Rates (IBOR) and General Collateral repo rates are taken from Bloomberg. Commercial paper (CP) rates for three different rating categories – A-1+/P-1, A-1/P-1 and A-2/P-2 – are obtained from TradeWeb, thus capturing funding cost heterogeneity in tiered non-bank funding markets. We also collect data on the bid quotes of T-bill

[24] A comparison with firm (and traded) quotes in Table 2 shows that the bid-ask spreads in the two segments are fairly close to each other. This suggests that the indicative swap quotes share less of the shortcomings of indicative quotes known e.g. from FX spot market studies.

rates (from Bloomberg) and central bank (CB) deposit rates. Among these, IBOR, CP and CB deposit rates naturally have a daily quoting frequency.

Descriptive statistics for the interbank deposits, IBOR, OIS and GC repo rates are reported in Table 3. The table comes in two parts, one for USD money market rates and one for EUR money market rates. Panel A shows descriptive statistics for spreads over OIS-rates. Panel B shows correlations between the four types of interest rates, both for levels and changes. The simple message is that the different money market rates behave quite differently, both in level and in changes. Hence, the choice of interest rate clearly matters.

[Insert Table 3 about here]

These data are complemented with other data sources to provide a more in-depth analysis of CIP deviations. We use primary market data on the issuance of certificates of deposits (CD) in U.S. dollars. CDs have similar characteristics as Commercial Paper in that they represent vehicles for unsecured wholesale funding from non-banks. CD issuance is subject to the requirement that the issuing bank be located in the U.S., either by subsidiary, branch or head office. This makes the use of CDs less flexible for funding purposes compared to CP issuance. However, as we will see below, these data will help understand the dispersion in funding rates and the potential for arbitrage.

II. Term funding liquidity premia

As argued above, CIP arbitrage needs to be examined based on interest rates that appropriately reflect banks' marginal funding costs. The unsecured marginal funding cost of bank j in U.S. dollars, $r_{j;\$}$ (suppressing the t subscript), can be represented 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 U.S. dollars.

A commonly used proxy for the risk-free rate in the equation above is the rate on Overnight

Indexed Swap (OIS).[25] However, OIS rates do not reflect *term funding liquidity* premia, rendering them unsuitable as measures of arbitrageurs' marginal funding costs. The CIP concept requires the arbitrage to be self-financed. In addition, it should not involve any risk for the arbitrageur. For this to be the case, the arbitrageur has to raise unsecured capital of the same tenor as the FX swap and invest the proceed in a risk-free asset. As we show below, cross-currency trades exploiting the cross-currency deviations in OIS rates gives rise to funding liquidity risk. Likewise, a trade based on GC repos does not account for the cost of funding the collateral, as outlined in Appendix B.

A. Cross-currency basis with OIS rates

Figure 2 illustrates the evolution of the cross-currency basis with OIS rates for various currencies (adjusted for transaction costs). The potential trading profits appear large in economic terms.

[Insert Figure 2 about here]

A similar picture emerges from Table 4, which shows the median OIS cross-currency basis for different key currencies. The Table presents results for two sample periods, the period of the GFC and the European sovereign debt crisis (January 2007 – December 2012), and the post-crisis period (January 2013 – December 2015).[26] We look at two directions of potential round-trip arbitrage: i) borrowing directly in foreign currency and swapping into USD ($FCU \Rightarrow USD$); and ii) borrowing directly in USD markets and swapping into foreign currency ($USD \Rightarrow FCU$). We carefully adjust for transaction costs in all legs of the trade as outlined in the previous section. Besides the median and standard deviation of the corresponding round-trip cross-currency basis, the Table also reports information on the persistence of the alleged arbitrage opportunities. It reports the proportion of day, weeks and months (consecutive days) over which the basis indicates trading profits.

All in all, results for the round-trip cross-currency OIS basis reported in Table 4 indicate significant trading profits from borrowing in USD markets and swapping into CHF, EUR and JPY. For

[25] An OIS 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, only the net difference between the realized overnight rate during the term of the contract and the agreed fixed rate.

[26] We do not show results for a pre-crisis sample, as evidence by Akram, Rime, and Sarno (2008) shows that CIP used to hold to a close approximation prior to the crisis.

the JPY and CHF, these have persisted over the entirety of the post-crisis sample period. Median arbitrage profits also appear for GBP and CAD, yet to a lesser extent.[27]

[Insert Table 4 about here]

Employing OIS rates for CIP calculations, however, suffers from the problem that OIS rates do not properly account for funding liquidity premia and leaves the arbitrageur exposed to rollover risk. It is important to keep in mind that it is not possible to raise funding through an OIS contract. In fact, the use of OIS-rates in CIP arbitrage (implicitly) assumes a highly complex sequence of trades:[28]

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.

There are at least three reasons why a non-zero OIS cross-currency basis does not necessarily indicate the existence of CIP arbitrage: (i) the actual overnight rate faced by the arbitrageur in the borrowing and lending currencies may deviate from the respective underlying overnight rates in the OIS contracts, (ii) the potential spreads between the underlying overnight rates in the OIS contracts and the actual overnight rates are uncertain during the term of the OIS contract, and (iii) by selling the borrowing currency spot on the expectation of obtaining it back at a later date

[27] The case of the Australian dollar which shows a reverse sign than the other currencies is interesting, as also emphasized in Du, Tepper, and Verdelhan (2016). Taken at face value, Table 4 suggests that it is profitable to fund arbitrage trades by borrowing at AUD rates, swapping into USD and placing them at the USD OIS rate. Even though not analysed further here, greater profitability could be achieved when coupled with a second swap of USD into JPY and placement of the funds in Japanese money markets.

[28] This mechanism is illustrated in Figure A.3 in the Online Appendix.

– but without securing this currency need by a loan covering the whole term of the FX swap (in this specific case rolling over O/N funding in order to lend out in the FX swap market at a longer tenor) – the arbitrageur effectively has taken on *funding liquidity risk* in the borrowing currency.[29]

The latter point is crucial since the arbitrageur seeking to exploit the OIS cross-currency basis effectively alters its composition of liquidity risk across the two currencies. The arbitrageur gives a longer-term loan (FX swap) than the term of the funding in one currency, and borrows at a longer term than that of the investment in another currency. When the term funding liquidity premium is relatively high in the currency where the arbitrageur is exposed to roll-over risk, this premium can be exploited in principle, but only at the expense of additional liquidity risk. Moreover, if the term of the FX swap is greater than 30 days, engaging in the trade will lower the liquidity coverage ratio (LCR) in the borrowing currency and increase it in the lending currency. Although not implemented in most of the currencies, fulfilment of currency-specific LCR requirements is a recommendation under Basel III and banks tend to put weight on the currency-specific LCR.[30]

B. Isolating funding liquidity premia

The arguments above suggest that it is not straightforward to interpret common measures of the cross-currency basis based on OIS (or GC repo) as risk-less arbitrage profits. Instead, the may reflect differentials in term funding liquidity premia across currencies.

Drawing on a panel of bank-by-bank data on quoted interbank deposit rates across different currencies further allows us to construct simple proxies for liquidity premium differentials vis-à-vis the U.S. dollar.[31] The goal is to isolate the liquidity premia, $\widetilde{lp}_{\$}$, in Equation (4) for marginal unsecured funding rate facing bank j. To do this, we first match the quote by a specific bank in one currency with that of the same bank in another currency. Such matching of individual quotes across currencies enables us to effectively remove the credit risk component as the same bank faces the same credit risk across all currencies. For each bank, we then take the difference between funding

[29] A more detailed analysis and discussion of the rollover risk is provided in the Online Appendix.

[30] Moreover, the total LCR may be reduced due to the 75 percent cap on the coverage of outflows. This means that only 75 percent of outflows can be covered by inflows. If this cap is binding, the outflow created by borrowing funds O/N can only be matched by 75 percent of the inflow from the O/N lending. That is, if the cap is binding, the bank has to increase the amount of liquid assets in order to maintain its liquidity ratio. This effect is independent of the term of the arbitrage trade.

[31] Interbank deposit rates are indicative quotes made by a selection of banks indicating the price they are willing to lend and borrow cash to/from another bank on unsecured basis

rate spreads over the risk-free rate (which we approximate by the OIS rate) in the two currencies. As credit risk is bank- but not currency specific, taking the difference across currencies strips out the credit component (cr_j in Equation 6) from funding spreads. By averaging across the set of banks J_t

$$\widetilde{lp}_{\$} - \widetilde{lp}_{\star} = \frac{1}{J_t} \sum_{j=1}^{J_t} \left[\left(r_{j;\$} - r_{\$}^{OIS} \right) - \left(r_{j;\star} - r_{\star}^{OIS} \right) \right], \tag{5}$$

we hence extract the *relative* funding liquidity premium between USD and the foreign currency.

Figure 3 (Panel a) depicts the joint evolution of the average cross-currency basis with OIS rates between USD and the six currencies and the average liquidity premium differential across currencies vis-à-vis the U.S. dollar. The latter is constructed as in Equation (5) outlined above.

[Insert Figure 3 about here]

Figure 3 shows that the funding premium differentials across currencies and the OIS-based cross-currency basis are highly correlated. When the term funding liquidity premium in USD are elevated, a marked rise in alleged CIP arbitrage opportunities can be observed if one looks at the OIS cross-currency basis. This is further confirmed confirmed in Panel (b) as an average across all currencies and both pre and post-crisis, and in Panel (c) for separate currencies for the period after the GFC. And, similar patterns can be observed in key non-bank funding markets as well. Panel (d) of Figure 3 shows that CP-OIS spreads have been significantly greater in the USD than in other currencies, irrespective of the credit rating. The gap between direct USD funding costs from non-banks and the equivalent in other currencies has considerably widened from Q2 2014 onwards.

The fact that fluctuations in measures of U.S. dollar term funding liquidity premium closely match those in cross-currency basis, indicates that funding strains in U.S. money markets are a primary driver. It suggests that arbitraging the OIS cross-currency basis may not be fully risk-less.

III. Law of one price violations and CIP arbitrage

We now turn to our empirical study of law of one price (LOOP) violations and CIP arbitrage profits in international money markets, drawing on money market rates that are consistent with the marginal funding costs of the main potential arbitrageurs.

A. LOOP violations in international money markets

Interbank rates. Table 5 presents results on LOOP deviations with IBOR and interbank deposit rates. In row (i), the direct borrowing costs in USD markets are compared against the costs of raising funds in foreign interbank markets and swapping into dollars. Row (ii) compares the direct borrowing costs in foreign money markets against the costs of borrowing in USD and swapping into foreign currency. In this context, we are not looking at a self-financed risk-less arbitrage strategy, but rather at relative value in funding options.

The following discussion primarily focusses on the post-crisis sample period, where FX swap market pricing has proven particularly puzzling. Panel A of the table points to LOOP deviations based on IBOR-rates for euro, Swiss franc and yen in the range of between 12 and 15 basis points on average over this sample periods (row ii). U.S. dollar LIBOR swapped into euro, Swiss franc or yen has resulted in a lower interest rate than the actual IBOR rate in the respective currencies. These LOOP deviations (also documented in prior work) have been fairly persistent and sizeable.

[Insert Table 5 about here]

The main takeaway from Table 5 is that LOOP deviations are reduced significantly if quoted interbank deposit rates are considered (Panel B). LOOP deviations for the three above-mentioned currencies are much smaller in economic terms, around just 1/10th, than those for IBOR rates. Finally, note that all positive deviations stem from swapping USD to the respective currencies.

A main reason why LOOP violations based on interbank deposit rates are fairly small is how banks price funds internally, a practice called Funds Transfer Pricing (FTP).[32] The internal fund transfer price determined by the bank's treasury unit across currencies is usually set such that the pricing is consistent with that in the FX swaps market. The reasons are two-fold. On the one hand, the bank's treasury needs to make sure that different business units are not engaging in *internal* arbitrage of funding cost differentials. On the other hand, the bank wants to avoid that deposit rates are priced such that they offer any arbitrage opportunities for competitors. If quoted interbank deposit rates reflect the internal price charged by the treasury unit, LOOP should hold fairly well. Our results reported in Table 5 support this interpretation.

[32] A detailed discussion of the institutional details behind FTP is provided in Appendix C.

Commercial paper. Table 6 reports LOOP deviations based on commercial paper rates. The general setup follows that of Table 5. We consider CP funding costs covering the credit spectrum in the CP market (based on short-term credit ratings). As can be gleaned from Table 6, LOOP violations based on CP rates are significantly lower (in absolute terms) than LOOP deviations for IBOR rates. This holds across the three rating buckets considered.

[Insert Table 6 about here]

B. CIP arbitrage in international money markets

We now turn to our main analysis of CIP arbitrage strategies in a world of segmented money markets. To examine the validity of the CIP criterion, we compare the FX swap-implied borrowing rate to the return on (close to) *risk-free* investment vehicles in a range of non-U.S. currencies.[33] For the funding leg, as stressed above, we again consider rates reflecting the marginal funding costs of banks. As vehicles for the investment leg of the CIP trade, we consider (i) short-term government paper (T-Bills), and (ii) central bank deposit facilities. This choice is in line with the basic requirements for arbitrage, namely that the investment be risk-free and implementable in practice.[34]

To capture funding costs for the arbitrage in a realistic manner, CP rates are our preferred choice. The reason is that unsecured interbank money market activity has essentially dried up in major currency areas since the crisis and hence is not how banks fund themselves anymore. Due to data availability of high-quality data for CP rates, only results for the post-crisis sample period are shown. Yet, this is the most interesting period where explaining developments in FX swaps pricing has proven particularly challenging. We examine potential arbitrage opportunities for various types of banks, according to their short-term credit rating.

[Insert Table 7 about here]

[33] 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).

[34] Note that the arbitrage trade studied above (investing in risk-free assets) does not bind any capital for banks. However, as emphasized in Sushko, Borio, McCauley, and McGuire (2016), some counterparty risk is inherent in the FX swap transaction itself despite collateralization. However, so-called two-way Credit Support Annex (CSA) agreements that are standard in FX swaps reduce the capital cost significantly and hence these costs are not very relevant for the maturities studied in this paper. Furthermore, the capital cost faced by dealers when entering into an FX swap is embedded in bid/ask spreads.

Table 7 presents results with T-Bills as the risk-free investment vehicle. First, we consider USD funding costs in CP markets 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 top-tier banks in their CP issuance) can still be considered as fairly creditworthy institutions, relative to many other financial institutions which do not have access to the CP market in the first place. The lower Panel of Table 7 shows that hardly any arbitrage profits can be reaped for A-2/P-2 banks. The notable exception is the Japanese yen, where arbitrage opportunities have been manifesting themselves over the last part of 2015.

[Insert Table 8 about here]

Table 8 depicts CIP arbitrage profits, based on borrowing in USD CP markets and placing the swapped funds in foreign central banks' deposit facilities. The lower Panel of the Table shows that some arbitrage profits have been available even for A-2/P-2 banks in the Swiss Franc and the Japanese yen. These are fairly small in economic terms, though, at 0.5 to 4 basis points on average over the post-crisis sample period. The upper panel indicates that significant arbitrage profits have been available for the set of top-rated global banks with good access to funding in U.S. dollar markets. For this set of players, economically viable arbitrage opportunities appear in sterling, yen, Swiss franc and euro. These arbitrage profits are as high as 18.8 basis points on average, if the funds are placed at the deposit facility of the Bank of Japan.

It is striking that arbitrage profits are much larger involving CB deposit facilities (Table 8) than when investing in T-Bills (Table 7). What explains these differences? The main driver is that the T-bill rate responds to the term liquidity premium in the respective currency, while the CB deposit rate is insensitive to the volumes placed in the central bank facility. Markets are segmented in that only a selected group of financial institutions has access to the deposit facility. Hence, the rate of remuneration of excess reserves does not apply to all market participants and may therefore not act as a solid anchor for the FX swap price at all times. On the other hand, the T-Bill rate is able to adjust to demand and supply imbalances. If a cross-border arbitrage opportunity combining an FX swap and T-bills shows up, one would expect both the FX swap price and the T-bill rate to respond to the corresponding price pressure.

C. Interim summary

The previous two sections demonstrated several striking features of international money markets in the post-GFC environment: (i) Term funding liquidity premia have evolved differently across the main currency areas, with USD premia being particularly elevated. As we argued above, this development has been an important driver behind the widening FX swap basis constructed from OIS rates. (ii) A narrow set of global banks has enjoyed *risk-less* CIP arbitrage opportunities in this environment. As we have shown above, access to USD funding from non-banks (in particular money market funds) at attractive rates is critical – coupled with access to safe investment vehicles in foreign currency, more specially CB deposit facilities. (iii) There is an important asymmetry between top-rated and lower-rated banks, as shown in the analysis of LOOP-deviations in Table 6.

IV. FX swap market equilibrium

The fundamental question arises how a situation with risk-free arbitrage profits for a narrow set of banks can persist over an extended period of time? We approach this question by studying the challenge faced by an intermediary in matching flows by different players in the FX swap market.

Three major forces have led to a shift in the FX swap market equilibrium and thus have affected the challenge faced by intermediaries: (i) implementation of QE and the abundance of central bank reserves has affected funding liquidity conditions differently across key currency areas; (ii) segmentation of international money markets and substantial tiering across banks has manifested itself in a large degree of funding cost heterogeneity, especially in the U.S. dollar; (iii) effective limits to arbitrage, in particular the difficulty to scale the arbitrage due to quantity constraints in the supply of USD funding by non-banks.

A. The impact of excess liquidity and segmentation

A good starting point for the analysis is the following equation (based on Equation (4))

$$\frac{F}{S} \approx \frac{1 + r^f_\$ + \widetilde{cr}_\$ + \widetilde{lp}_\$}{1 + r^f_\star + \widetilde{cr}_\star + \widetilde{lp}_\star}, \tag{6}$$

suggesting that (under normal circumstances) the FX swap-implied interest rate differential equalises interest rate differentials in money markets. Prior to the GFC and central banks' reliance on unconventional monetary policies, credit-premia $\widetilde{cr}$ for equally risky banks were small and reasonably aligned across countries. Similarly, liquidity premia $\widetilde{lp}$ were relatively small and roughly equal across currencies.

Figure 4 sketches four possible states of the FX swap market. Panel (a) illustrates how, under a normal market environment, a single swap-rate can maintain the law of one price (LOOP) across banks with different credit ratings. The two vertical lines indicate the level of interest rates in the two countries ("US" on the left-hand side and "Foreign" on the right-hand side). Different levels of funding rates are marked at the vertical lines. For simplicity, we look at three different levels of funding rates (top, mid, low). The slope of the curve connecting interest rates in the two currency areas is the FX swap-implied interest rate differential, that is, the (log) forward/spot-ratio F/S. If LOOP holds, this line will connect the two interest rates since $(1 + r_{\$}) = \frac{F}{S}(1 + r_{\star})$. If the vertical distance between the different interest rates is the same, e.g. when credit 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.

We argue that the balance in FX swap markets has been significantly distorted by the excess liquidity due to QE in major currency areas. In recent years, central banks in the largest currency areas outside of the U.S. (in particular, euro area and Japan) have implemented large asset purchase programs, where financial institutions selling securities have been credited with a large amount of central bank reserve balances. Large part of this liquidity in excess of minimum reserve requirements has been placed in central banks' deposit facilities.[35]

[Insert Figure 4 about here]

This has meant that the marginal funding costs of banks domiciled in the corresponding QE countries have effectively dropped to the rate of remuneration of CB deposit facilities. Banks at

[35] The floor system for the Swiss franc exchange rate against the euro operated by the Swiss National Bank between 09/2011 - 01/2015 (and also subsequent heavy FX interventions) effectively led to a similar situation.

the bottom of the credit spectrum have benefited disproportionately from this situation.[36] To raise funds in EUR for instance, a European bank can simply tap its excess reserves placed in the deposit facility of the ECB/Eurosystem. This has in turn led to a substantial fall of liquidity premia in the affected currency areas, $\widetilde{lp}_\star$ in Equation (6), and a compression of marginal funding costs to deposit facility rate. By contrast, U.S. dollar liquidity premia, $\widetilde{lp}_\$$, have remained elevated in large part due to a structural demand for U.S.-funding by global banks.

The implication is that it has become impossible for 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. Panel (b) of Figure 4 illustrates the impact of excess liquidity on the compression of banks' marginal funding costs. The previous bank-specific foreign marginal funding costs, now in italics, are no longer binding in this situation.

B. Implications for FX swap market intermediaries

To understand the configuration in FX swaps and international money markets, it is useful to take the perspective of the key intermediaries in this market and to recapitulate their main incentives and institutional constraints. A market maker's primary objective is to earn from bid-ask spreads, while taking as little as inventory risk as possible (Evans and Lyons, 2002). When an FX swap dealer enters into a transaction with a counterparty, its alternatives are threefold: (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 – 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 over-night risk limits that effectively force the market makers to end the day "flat".

In the environment described above, the challenge of the swap market maker is to map a single non-U.S. rate onto a distribution of U.S.-rates using a single swap-rate, under the constraint to maintain a zero (or constant) inventory, at least in expectation. Any quote of FX swap points set

[36]For instance, when the central bank conducts longer-term operations with full allotment against a broad array of securities at a fixed rate, banks that face substantially higher market funding costs due to elevated credit risk have a strong incentive to take advantage of the funds provided by the central bank. In a similar vein, implementation of asset purchase programmes comes hand in hand with an inflow of deposits from the non-bank sector (especially pronounced in combination with negative interest rates) and large amounts of central bank reserves remunerated at the terms decided by the central bank.

by the dealer will imply a profitable opportunity for at least one set of swap end-users, but the question is which types of players enjoys such opportunities in equilibrium.[37]

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 top-tier banks and the foreign central bank's deposit facility rate. In Panel (b) 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. With these price quotes, top-rated banks would not face any CIP arbitrage opportunities. Yet, this quote of the swap price cannot be an equilibrium rate because all banks with more costly direct funding in USD could obtain dollars more cheaply via the swap-market than through direct borrowing. A LOOP violation would arise for the bulk of banks' with inferior ratings, indicated by arrows going from foreign rate to the U.S. rate. In this scenario, the market maker would face a highly one-sided demand pressure for U.S. dollars and would accumulate a large inventory.

An equilibrium swap-implied rate differential must be set such that LOOP holds for the majority of banks that account for the bulk of U.S. dollar demand. This is indicated by the solid red line marked by zeros in Panel (c) of Figure 4, 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).

The implied swap flows supporting this as an equilibrium are shown in Panel (d). The line mapping the USD funding rate faced by top-rated banks onto the marginal funding rate in foreign currency implies an FX swap-implied funding rate in foreign currency that is lower than that on the CB deposit facility. Thus, banks facing U.S.-funding costs at the most attractive rates obtain a CIP arbitrage opportunity involving USD unsecured funding and placing the funds with foreign central banks. Consequently, this line is marked with arrows going from U.S. to Foreign. At the same time, banks that would face more costly direct funding in U.S. dollars than mid-tier banks, may find it more attractive to raise USD funding indirectly via the swap-market. The flow of this group of banks is depicted via the line next to the LOOP-line for mid-level banks, with arrows pointing into the USD direction. This does not represent CIP-arbitrage, but rather an opportunity

[37] It is important to keep in mind that some of the market maker's customers could also be internal units in the same institution that need to trade FX derivatives. This could for instance be the bank's asset management unit that needs to enter into FX forwards or swaps in order to hedge, or the Treasury unit who may need to rely on swaps to raise wholesale funding.

for banks at the bottom of the credit spectrum to swap parts of their abundant reserve balances into foreign currency in order to fund USD assets (i.e. a LOOP-deviation).

In sum, Figure 4 Panels (c) and (d) sketch the new FX swap market equilibrium in a world of segmented money markets and excess liquidity. A narrow set of banks enjoys CIP arbitrage gains while a another set of banks enjoys cross-currency funding opportunities. The swap dealer quotes prices such that any USD demand/supply imbalance is absorbed and the corresponding risk appropriately shared between different groups of end-users.

C. Impediments to Arbitrage

There are several further important institutional features that help explain why a constellation with risk-less arbitrage opportunities for some players in international money markets can persist.

First, the set of possible arbitrageurs with access to U.S. dollar funding at attractive terms is fairly contained. Global banks domiciled outside the U.S. have a structural USD demand to serve their corporate and financial clients and fund dollar assets. Many of these banks, however, have very limited access to insured retail USD deposits and thus are forced to raise funding by market instruments directly in USD or through the FX swap market. This also is one of the explanations why the funding premium in U.S. dollar has remained elevated despite large-scale asset purchases conducted by the Federal Reserve and the large amount of central bank reserves available to the banking system. And, as shown in Table 9, a significant share of the largest global banks typically faces a worse credit rating than the top-rated global banks (A-1+/P-1). This translates into prohibitively high marginal costs of obtaining USD funding for the majority of banks.

[Insert Table 9 about here]

Furthermore, even within the group of highly rated banks, the actual funding costs may differ significantly. Figure 5 shows the rates at which top-rated banks issue CDs in the U.S. market (in dots), together with the highest U.S. funding cost necessary for being able to engage in CIP arbitrage (solid line). The blue dots represent CD-rates for Asian banks, while red dots represent CD-rates for banks from advanced economies. There is a large dispersion in the rates at which these banks can obtain unsecured funding, and in many cases the CD-rates of the Asian banks are higher than these threshold rates, suggesting that not all top-rated banks can engage in CIP arbitrage.

[Insert Figure 5 about here]

What is preventing U.S. banks to deploy arbitrage capital? Among the banks in our 3-month CD data, U.S. banks are close to non-existent. However, these banks have good access to USD through other sources, such as retail deposits (covered by deposit insurance). In principle, U.S. banks thus serve as a potential source of USD provision in the FX swap market. However, due to the leverage ratio they require a relatively large arbitrage return in order to extend their balance sheet solely for the purpose of the arbitrage trade. For example, a leverage ratio requirement of six percent and a required return on equity (RoE) of 10 percent, a back of the envelope calculation suggests that a 60 basis points return on the arbitrage trade is needed to render it attractive.

Second, not all global banks have a flexible balance sheet. Many large global banks domiciled outside of the U.S. have a significant amount of USD assets to fund, which is a profitable business in itself. In turn, this raises the "hurdle" for allocating USD funds for arbitrage activities in international money markets. Some smaller global banks and those with a smaller USD portfolio to fund, by contrast, may have a more flexible balance sheet composition mostly consisting of high quality liquid assets in USD. It is particularly these more nimble global banks that can reap the arbitrage opportunities documented in the previous section.

Third, potential arbitrageurs face quantity limits with regard to direct USD wholesale funding, which in turn makes the arbitrage difficult to scale. At the short-end of the USD marginal cost curve (below 1-year), money market funds (MMFs) are the dominant investor in securities issued by banks. To avoid concentration risk, MMFs have strict limits regarding the amount they are willing to invest with each counterparty. This puts a quantity limit on banks' ability to raise dollar funding in the U.S. CP market.[38]

Fourth, regulatory and internal constraints can also act as impediment to CIP arbitrage. The impact of regulation is fairly subtle, however. The investment vehicles in the CIP arbitrage trades we investigate in our main analysis, T-Bills and CB deposits, feature zero risk weights and hence the bank's capital ratio is not affected. For short-dated swaps, capital charges for counterparty

[38]Furthermore, the cost of CP funding increases with the amount each counterparty seeks to raise. This feature is not reflected in the CP rate data from TradeWeb used above.

risk should also be fairly insignificant (if the counterparties have agreed to two-way CSA). The supplementary leverage ratio (SLR) may bind at key reporting dates (year-end and quarter-end) and affect short-dated swaps, but otherwise it should not be an impediment for arbitrage activity.[39] Finally, for trades where the funding and investment vehicles share the same maturity, as would be the case in the CIP-arbitrage in Section III, the liquidity position of the bank is not affected (at least from a multi-currency perspective).[40] Constraints from the liquidity coverage ratio (LCR) hence would not binding – unlike in the case of the OIS roundtrip trade covered in Section II.

Fifth, the distortions arising from the abundance of excess liquidity in certain currency areas discussed above are persistent. When the amount of excess reserves in the system increases, the marginal funding cost for banks operating in this currency is pushed down towards the rate of remuneration of reserves. Put differently, the large amount of reserves that appear on banks' balance sheets due to QE implementation have to be placed at the CB deposit facility, and the opportunity cost of using these reserves (e.g. to fund assets in foreign currency) then equals the rate on the CB deposit facility. Due to the LOOP funding opportunity, a critical mass of market participants faces incentives pushing their flow in the other direction than that of the main arbitrageurs.

D. *Evidence*

We now present some evidence consistent with the framework outlined above. In this context, we (i) revisit some of the results in Tables 7-8, (ii) discuss evidence on arbitrage activity involving the Bank of Japan's deposit facility, and (iii) study the impact of the ECB's asset purchase programme on the law of one price. When contrasting our framework with the data, the top-tier banks in Table 8 naturally represent those with the most attractive USD funding rates that enjoy CIP-arbitrage opportunities. Banks with inferior rating in the CP market (A-2/P-2), by contrast, appear not to enjoy any economically attractive arbitrage profits on average in the post-crisis period. We can think of these banks as representing the bulk of banks at the centre of the distribution whose funding

[39] Du, Tepper, and Verdelhan (2016) carefully demonstrate seasonality the FX swap market linked to key regulatory reporting dates, such as year-ends and quarter-ends. The seasonality is most evident in short-dated FX swaps and is also present in other money market segments.

[40] This would change if the LCR is applied by currency. While an application of the LCR on a by-currency basis is not mandatory under Basel III, many supervisors recommend that practice and banks may pay close attention to LCR figures by currency for their internal liquidity risk monitoring.

costs are in accordance with the law of one price.[41]

As shown by Table 8 in the previous section, most of the time, the CB deposit rate has acted as a "floor" for the FX swap-implied rate when we consider the U.S. CP rate for lower-tier banks as the marginal cost in USD. Moreover, at times when the floor created by the CB deposit rate is "leaking", the foreign T-bill rate has acted as a "hard floor" for the FX swap-implied rate. An interesting exception is the Japanese yen. The implicit yen rate when swapping funds raised via the USD CP market has been substantially below that on Japanese T-bill rate ever since mid-2015, not just for top-rated but also for lower-tier banks.[42] One reason may be that Japanese sovereign debt has been downgraded over the last couple of years and hence internal risk limits may bind.[43]

That said, one would expect that the pricing in FX swaps markets and the CIP arbitrage profits available by investing at the Bank of Japan's deposit facility has indeed attracted arbitrage capital. Figure 6 shows yen 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 yen holdings by top-rated banks, while those of all other global banks active in Japan are depicted in Panel (b). Blue bars represent the amount of net head quarter funding from abroad. Top-rated banks have bolstered up their holdings with the Bank of Japan substantially since the introduction of renewed Quantitative Easing in 2013, primarily financed by channeling funds from their head office. This is effectively exploiting arbitrage opportunities. Similar patterns cannot be observed for the set of banks that do not enjoy a top rating, as is evident in Panel (b).

[Insert Figure 6 about here]

This evidence is consistent with the prediction of the framework outlined above that banks with access to cheap funding in U.S. dollars do exploit the arbitrage trade. It is important to point out, however, that the availability of dollar funding for such trades is relatively scarce compared to the demand pressure resulting from the sheer amount of excess liquidity in yen. It further supports our

[41] A challenge when mapping the framework outlined above to the data, is that it is difficult to obtain data on marginal funding rates in the USD market for the set of worst-rated banks. There is a selection bias as these banks will prefer to use the swap-market when raising U.S. dollars. However, as we argue below, swap market order flow (into USD) may be used to proxy for demand imbalance created by banks with the lowest credit rating.

[42] As reported in Table 7, in a about one third of the days in our sample, the FX swap-implied rate for lower-tier banks is below the Japanese T-bill rate in the post-crisis sub-sample.

[43] At the time of writing, Japanese sovereign debt is rated A-1/A+/A by Moody's, S&P and Fitch, respectively. By contrast, German, Swiss, Australian and Canadian Sovereign debt is AAA rated.

view that the persistence of arbitrage opportunities is primarily due to funding liquidity constraints in USD and the relative access to funding across currencies.

Another case in point is how the introduction of QE in the euro area has perturbed the equilibrium in the FX swaps market for EUR against USD. Figure 7 shows that prior to the introduction of the ECB's public sector purchase programme, the interest rate differential implied by FX swaps lined up very well with the difference in CP rates for lower-tier banks across both currencies. In other words, LOOP held to a close approximation for this set of banks. Following the introduction of public sector asset purchases in January 2015, the FX swap-implied rate differential has gradually moved to equalize the difference between the lower-tier CP rate in USD and the ECB deposit rate. As we discussed above, the latter represents the marginal funding costs for banks awash with EUR reserve balances. This illustrates the impact of central bank actions on banks' marginal funding costs. And, it shows how FX swaps market acts as a shock absorber by adjusting to the changes in the effective marginal costs across currencies.

[Insert Figure 7 about here]

E. Imbalances in the FX swap market

To shed further light on the hypothesized mechanism, we now investigate the impact of imbalances in the swap market as captured by order flow. As mentioned above, swap dealers have a primary incentive to quote FX swap points so that (in expectation) they face a balanced order flow from end-users. However, when there are deviations between the funding costs by lower-tier banks across currencies, the FX swap market is out of equilibrium. We expect the price impact of swap order flow to be particularly elevated in these circumstances.

These situations can be analyzed using order flow. For this purpose, we rely on panel regressions of the form

$$\Delta CIP_{i,t}^{dev} = \alpha_i + \gamma \cdot CIP_{i,t-1}^{dev} + D_{i,t} \cdot \beta_{swapOF} OF_{i,t}^{swap} + D_{i,t} \cdot \beta_{LiqDiff} LP_{i,t} \\ + D_{i,t} \cdot \beta_{USD} \Delta USD_{i,t} + D_{i,t} \cdot \beta_{spotOF} OF_{i,t}^{spot} + \varepsilon_{i,t},$$

where we regress the change in CIP deviations onto a measure of FX swaps order flow $OF_{i,t}^{swap}$, and a set of control variables. The latter includes the lagged level of CIP deviation to capture the forces pulling any deviations back to zero (akin to an error-correction mechanism). Moreover, we also account for (changes in) funding liquidity premium differentials $LP_{i,t}$ (see Section II), spot order flow $OF_{i,t}^{spot}$, and spot returns $\Delta USD_{i,t}$ as suggested by Avdjiev, Du, Koch, and Shin (2016). All variables capturing the dynamics are interacted with dummies $D_{i,t}$ that indicate whether there is a deviation or not. Order flow is standardized and measured so that a positive number represents flow into the U.S. dollars at the spot leg, and and into foreign currency at the forward leg. Results for different sets of control variables are presented in Table 10.

[Insert Table 10 about here]

Our framework above suggests that in a situation with severe funding constraints in the market for U.S. dollar, lower-tier banks will raise U.S. dollars via the swap market. This will imply a positive swap order flow, i.e. flow into USD at the spot leg. In such a situation, the swap dealer will have to quote a higher swap-rate $F - S$, i.e. a steeper curve in Figure 4, in order to attract matching flow of opposite sign. Driven by a string incentive to balance its inventory, a CIP arbitrage opportunity needs to granted for top-tier banks that are less constrained in the USD market and are in a position to supply dollars to the swap market.

The positive coefficient on swap order flow in Table 10 confirms this intuition. A positive coefficient on the order flow variable can be interpreted as a 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). This evidence is an indication that larger price adjustments are necessary in order to equate the flows when the FX forward price deviates from what we define as equilibrium. We interact order flow with a dummy for whether there is a CIP deviation or not (differentiated by rating categories). In orderly markets, with no deviation, only a small change in $F-S$ is needed to curb a order imbalance, hence a small price impact of e.g. 0.4 bp in column (2) for a one standard deviation change in order flow. During periods when deviations are observed for A1-P1 banks, a positive order flow signals a worsening of funding constraints in USD money markets. In this case, the dealer would expect further demand pressure by lower-tier financial institutions to raise U.S. dollars in the swap market. To cope with this imbalance, a large adjustment of $F - S$ quotes is required to elicit offsetting arbitrage flow from top-tier banks. The price impact of 0.7

bp in Table 4, column (2), confirms this intuition. By the same token, if a positive order flow (into USD at spot leg) is observed in a situation when also deviations for banks with lower ratings occur (A-2/P-2 in Table 4), overall funding constraints must be even more severe. This requires an even greater adjustment in $F - S$ quotes by the dealer to restore FX swap market equilibrium, as indicated by the 2.7 bp price impact coefficient in column (3).

V. Conclusion

It has been suggested that Covered Interest Parity (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 of segmented money markets and heterogeneous funding costs across banks, the law of one price cannot hold any longer for the full set of interest rates simultaneously. Careful attention needs to be paid to select the appropriate interest rates and to account for all the costs and risks faced by a potential arbitrageur. Unpacking the true marginal funding costs faced by banks has become especially difficult. This has been further exacerbated by the abundance of central bank reserve balances resulting from unconventional policies, and their impact on banks' funding conditions in different currency areas. All this constitutes a major challenge for the main intermediaries in FX swap markets who have a strong incentive to quote prices such that they face a balanced order flow.

We find that the law of one price in international money market holds in fact remarkably well when considering money market rates that reflect banks' marginal funding costs. Risk-free and economically attractive CIP arbitrage opportunities do indeed exist – but only for a confined set of highly-rated global banks. Access to U.S. dollar funding from non-banks (in particular money market funds) at attractive rates is critical – coupled with access to safe investment vehicles in foreign currency, more specially central bank deposit facilities. Segmentation and funding cost heterogeneity thus matter significantly for market outcomes.

This raises the fundamental question of how a situation with risk-less arbitrage profits can persist over a prolonged period of time. We show that such a situation can indeed be part of an equilibrium outcome in a world of segmented money markets and excess liquidity. If an intermediary wants to avert facing an imbalance in order flow, its quotes need to entail some arbitrage opportunities for certain market participants. And, as we show in the paper, the price impact of FX swap order flow is particularly strong – and arbitrage profits greatest for top-tier banks – when lower-tier have an incentive to turn to the FX swap market to obtain U.S. dollar funding.

The evidence presented in this paper suggests that the main paradigm of CIP – risk-less arbitrage profits are non-existent after accounting for risk and transaction costs – still remains largely valid in post-crisis financial markets: arbitrage profits can only be enjoyed by a small set of players, but not by the vast majority of internationally active banks. As we argue in this paper, arbitrage capital is difficult to deploy on a large scale. Common measures of CIP deviations will thus likely continue to reflect money market segmentation, heterogeneity in marginal costs and funding liquidity premium differentials across currencies, rather than be an indication of a "free lunch".

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Appendix A: Transaction costs

This section lays out how we account for bid-ask spreads when computing CIP arbitrage profits or the cross-currency basis. 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, represented by $\overline{F^b - S^a}$ (here at bid), instead of (outright) forwards, we get the following expressions for deviations from CIP:

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

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

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).[44]

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 (A.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.

Appendix B: Cross-currency basis with repo rates

It has also become common to express alleged CIP arbitrage opportunities based on GC repo rates. Yet, as we argue in the following, similar to the case of OIS covered in the main text, the use of GC repo rates is not innocuous when the goal is to investigate CIP arbitrage opportunities.[45]

To make our point, we first revisit some basics. The difference between a collateralized loan and a repo is that the cash taker transfers the juridical rights of the collateral to the cash provider during the term of the repo. In a USD general collateral (GC) repo, one can raise USD cash by posting a predefined set of USD-denominated securities. The set of collateral in a GC pool is fairly homogenous and of good quality to protect the cash provider's counterparty risk exposure. Since the cash provider receives a security as collateral that is juridically owned by the cash provider, the overall liquidity loss by providing cash in a repo is limited. The cash provider knows that in case of any liquidity issues during the term of the repo, she can turn around and use the collateral in the GC repo market to raise the necessary liquidity (re-use of the collateral provided by the cash

[44]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.

[45]Figure A.5 in the Online Appendix illustrates the mechanism of using the repo market in CIP arbitrage.

taker). This means that the term funding liquidity premium that may be present in the unsecured funding market is less severe in the repo market.

Could arbitrageurs exploit any potential repo-based CIP-deviations as indicated by a non-zero cross-currency basis? The answer is yes, but only at the expense of giving up funding liquidity in the borrowing currency. By the same token, the arbitrageur will be liquid in the lending currency. The arbitrageur gives up assets that can be a source of funding through the repo market denominated in the currency featuring high term funding premia, but receives assets denominated in the currency featuring a low funding premium. The collateral used to receive cash in the borrowing currency, however, may have a higher unsecured marginal cost (value) than the collateral received in the investment currency. In such a situation, a non-zero cross-currency basis based on repo-rates do not constitute arbitrage opportunities. Rather, they are a reflection of cross-currency differences in the total costs of funding the collateral.

An important underlying assumption for the point above is that CIP arbitrage needs to be a self-financing strategy. A repo is a way of obtaining cash against assets that are initially financed by unsecured borrowing. To use a repo in a CIP arbitrage trade, the pledged collateral has to be unencumbered. Yet, unencumbered assets have an initial unsecured funding cost. This means the repo rate understates the true *marginal* funding cost of the trade – namely the unsecured borrowing cost. When there are differences in the spread between unsecured funding and repo rates across currencies due to differences in the term funding liquidity premium, the cross-currency basis for repo rates will reflect these premia. In principle, this problem can be mitigated if one invests in a repo and receives collateral with the *same* credit quality denominated in the same currency. A GC repo does not allow cross-currency collateral, though.[46]

Appendix C: 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). A schematic representation is provided in Figure A.6 in the Online Appendix. 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 banking 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 the 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

[46] A further discussion on repo-based arbitrage trades involving collateral denominated in different currencies is provided in the Online Appendix.

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 banks customers (liability side) and the internal price, and (ii) the spread between the internal 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. The marginal cost induced from interbank deposit rates includes banks' balance sheet costs. However, when interbank deposit rates do not fully capture the bank's marginal cost, a markup has to be added on top when determining the internal price.

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, as well as the credit risk premium of the quoting bank. And, they reflect the balance sheet cost of using

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

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

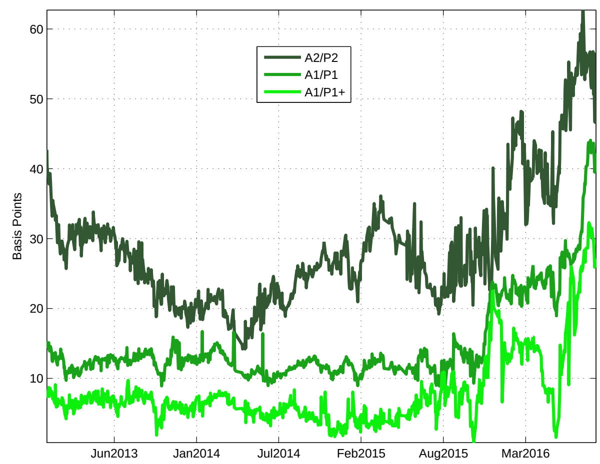
[49] For example, if the treasury pays business units more for currency A than it implicitly charges for the funds in currency B swapped into currency A by conducting an FX swap, business units may have an incentive to borrow currency B, conduct an FX swap in the market and sell currency A back to the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

[50] Of course, the treasury department may be in the position to look for 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 largely remain intact.

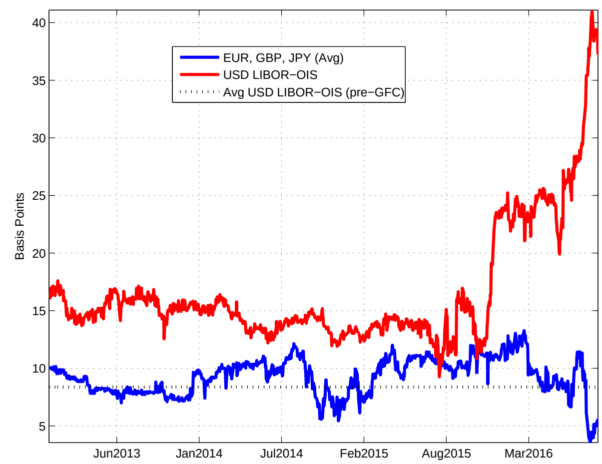
additional funds. Interbank deposit rates thus exactly capture what banks' funds transfer price ought to represent as well. One may therefore expect that there is a tight empirical relationship between interbank deposit rates and the funds transfer price.

Tables and Figures

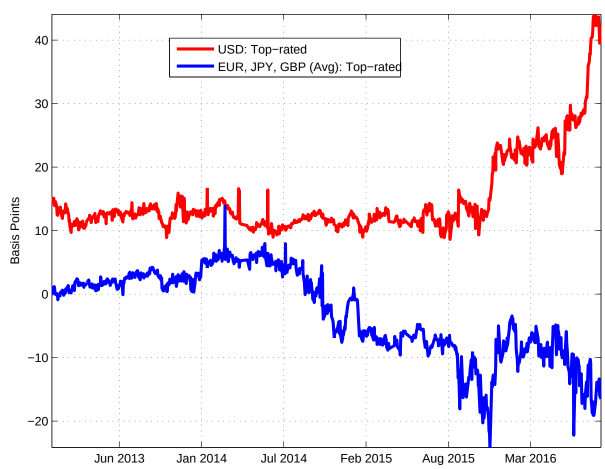
Figure 1
Segmented money markets



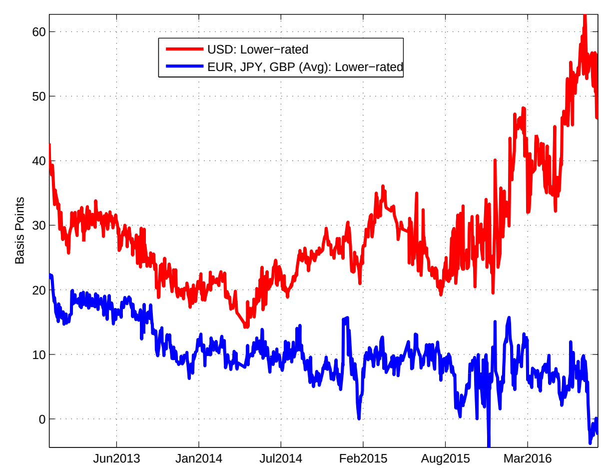
(a) USD CP spreads



(b) USD LIBOR-OIS vs other currencies



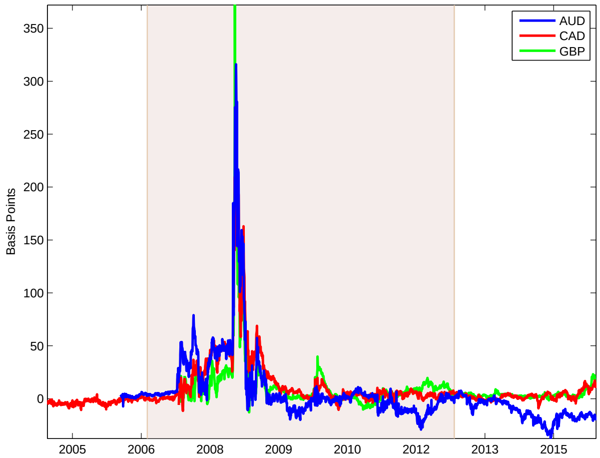
(c) CP-OIS top-rated banks (USD vs other currencies)



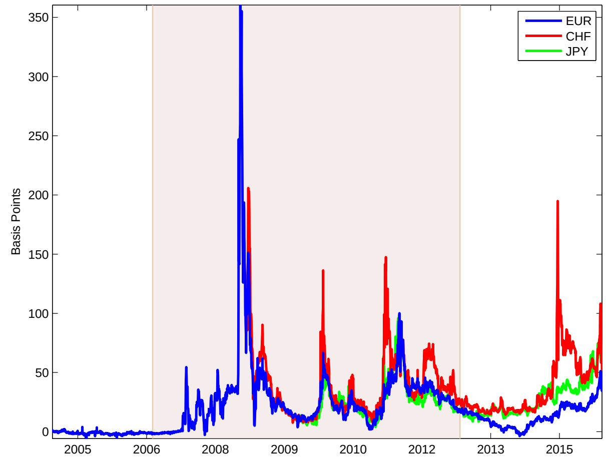
(d) CP-OIS lower-rated banks (USD vs other currencies)

Notes: The Figure depicts the evolution of money market spreads in USD and major foreign currencies in the post-GFC period. Panel (a) shows spreads of USD Commercial Paper over OIS rates for various rating buckets (best-rated: A-1+/P-1, top-rated A-1/P-1, lower-rated A-2/P-2). Panel (b) depicts the joint evolution of USD LIBOR-OIS and that of IBOR-OIS spreads for EUR, JPY and GBP (averaged across the three currencies). Panel (c) compares the evolution of CP-OIS spreads in the U.S. dollar to that in other major currencies (average for EUR, JPY and GBP) for top-rated banks. Panel (d) shows CP-OIS spreads in the USD to that in other major currencies (average for EUR, JPY and GBP) for lower-rated banks.

Figure 2
Cross-currency basis with OIS rates



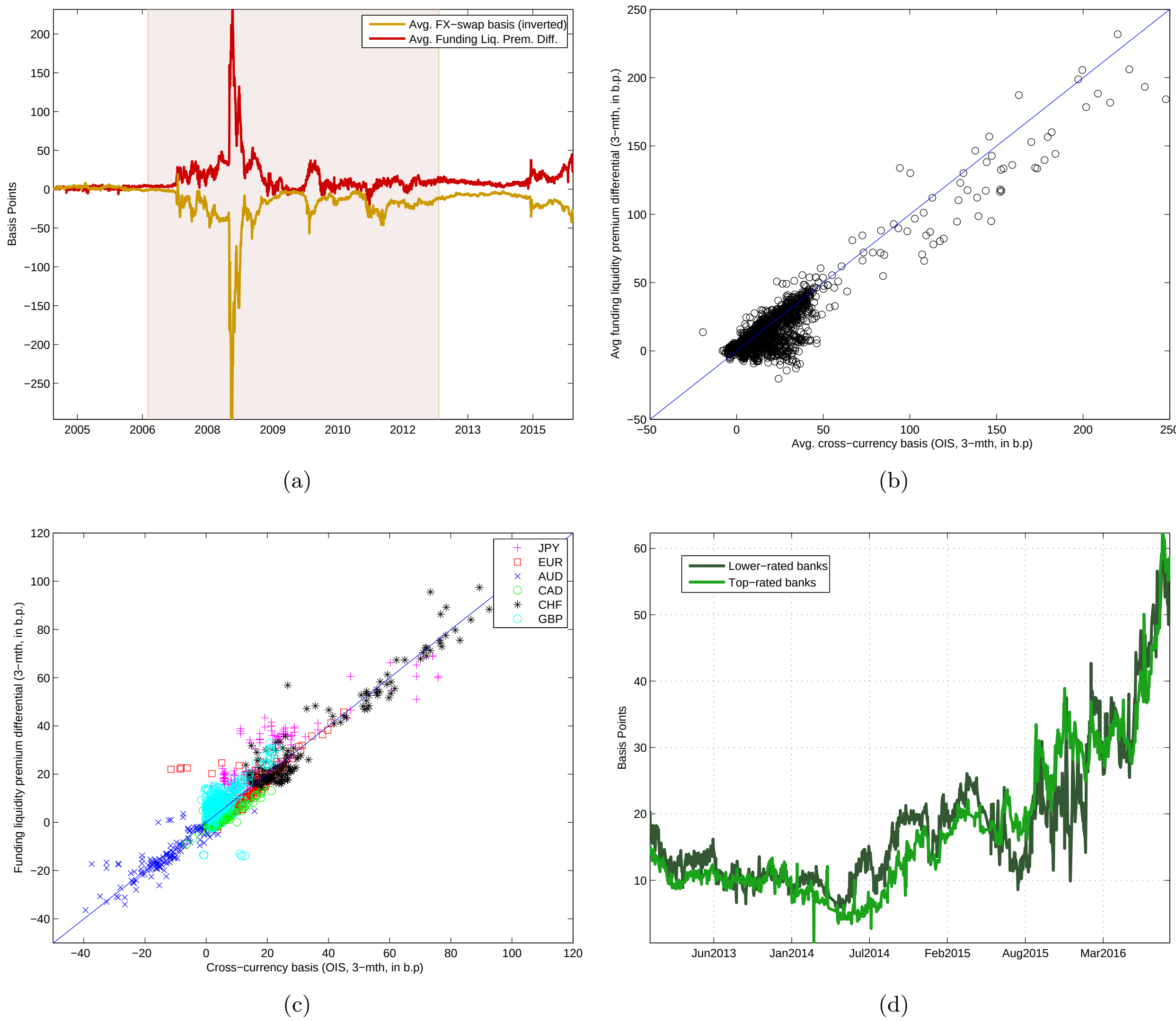
(a) AUD, CAD, GBP



(b) EUR, CHF, JPY

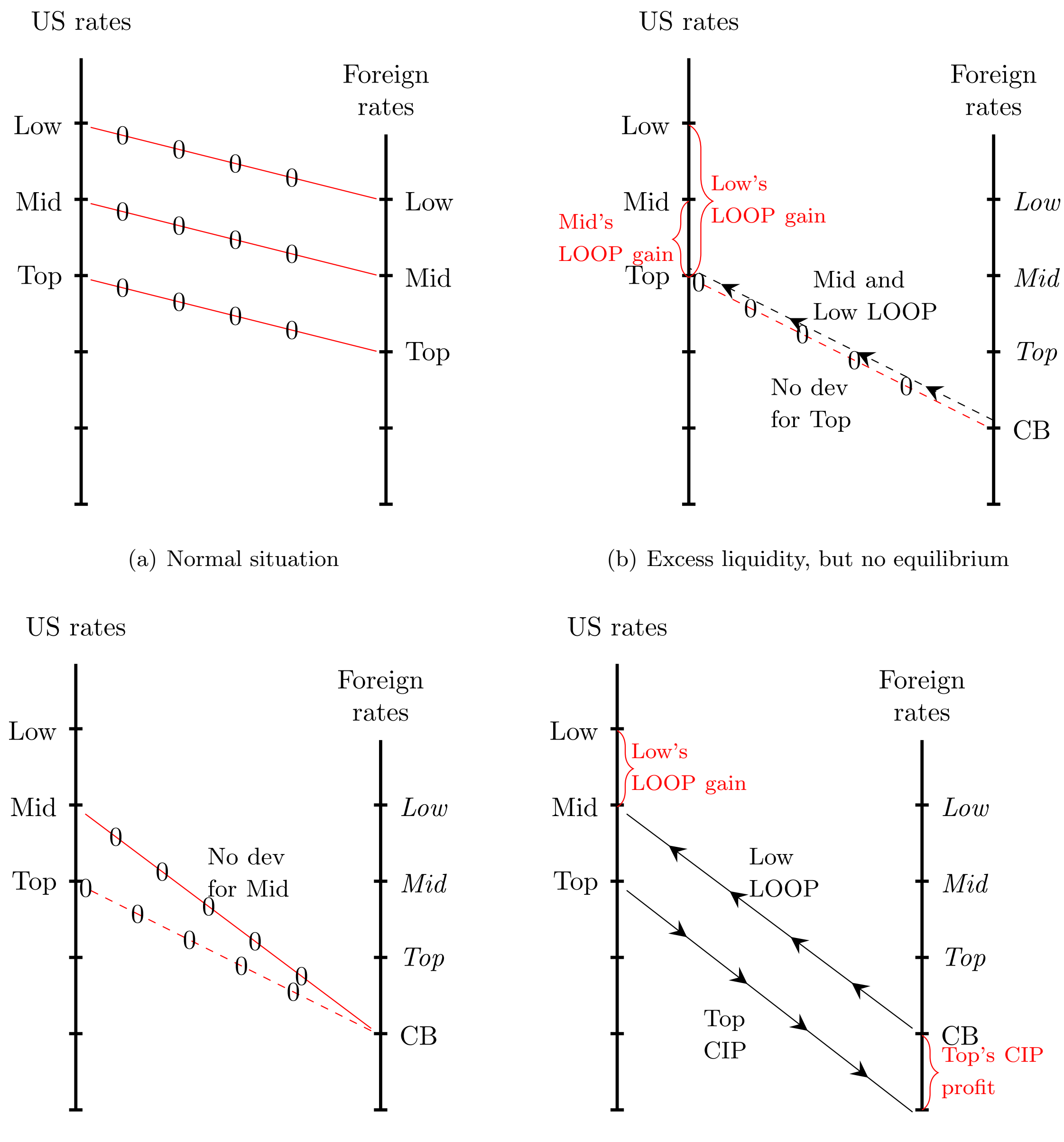
Notes: The Figure shows the evolution of profits from roundtrip cross-currency basis trades (measured in basis points) involving USD borrowing (USD interest rate at the ask-rate), using OIS-rates. All legs of the roundtrip cross-currency trade (rates and FX swaps) are adjusted for bid-ask spreads (as described in the text). Panel (a) shows trading profits for AUD, CAD and GBP, while Panel (b) depicts the similar profits for EUR, CHF and JPY.

Figure 3
Funding liquidity premia and the cross-currency basis



Notes: The Figure illustrates the relation between funding liquidity premia and the cross-currency basis calculated from OIS rates. Panel (a) shows the 3-month cross-currency basis based on OIS rates (averaged across the full set of currencies) together with funding liquidity premium differentials vis-à-vis the U.S. dollar. The latter are constructed based on a panel of interbank deposit quotes in multiple currencies as outlined in Equation (6 and averaged across currencies. Panel (b) shows a scatter plot of the average 3-month cross-currency basis and average liquidity premium differentials. Panel (c) presents a similar scatter plot for the GFC period, broken down by currency and aggregated to the weekly frequency. Panel (d) shows the difference in USD CP funding spreads (over OIS) relative to the average CP funding spreads in other major currencies (EUR, JPY, GBP). The comparison is performed for top-rated (A-1/P-1) and lower-rated (A-2/P-2) banks.

Figure 4
FX swap market equilibrium



(a) Normal situation

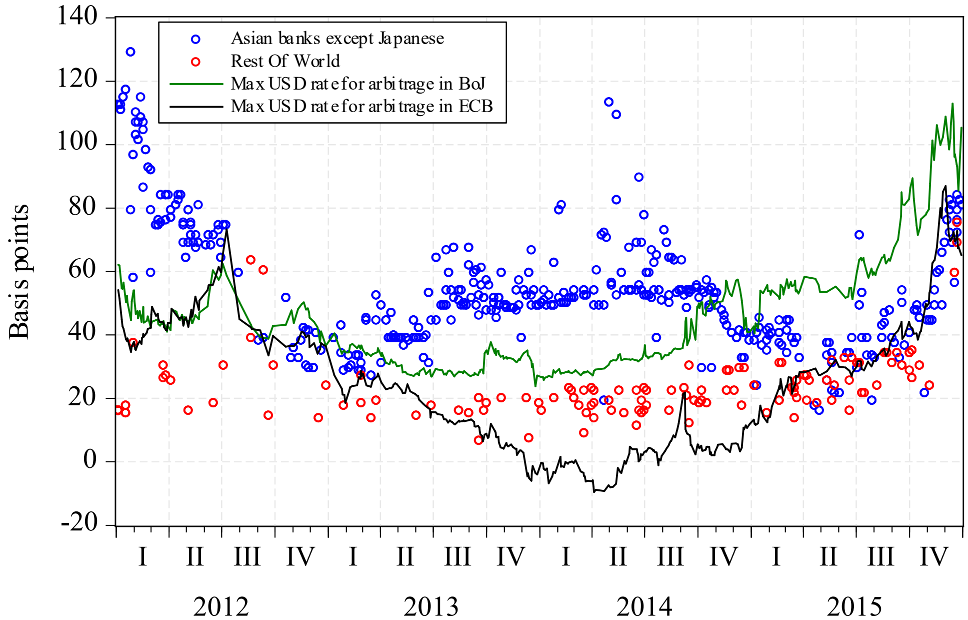
(b) Excess liquidity, but no equilibrium

(c) Excess liquidity: Equilibrium swap-rate

(d) Excess liquidity: Swap flows

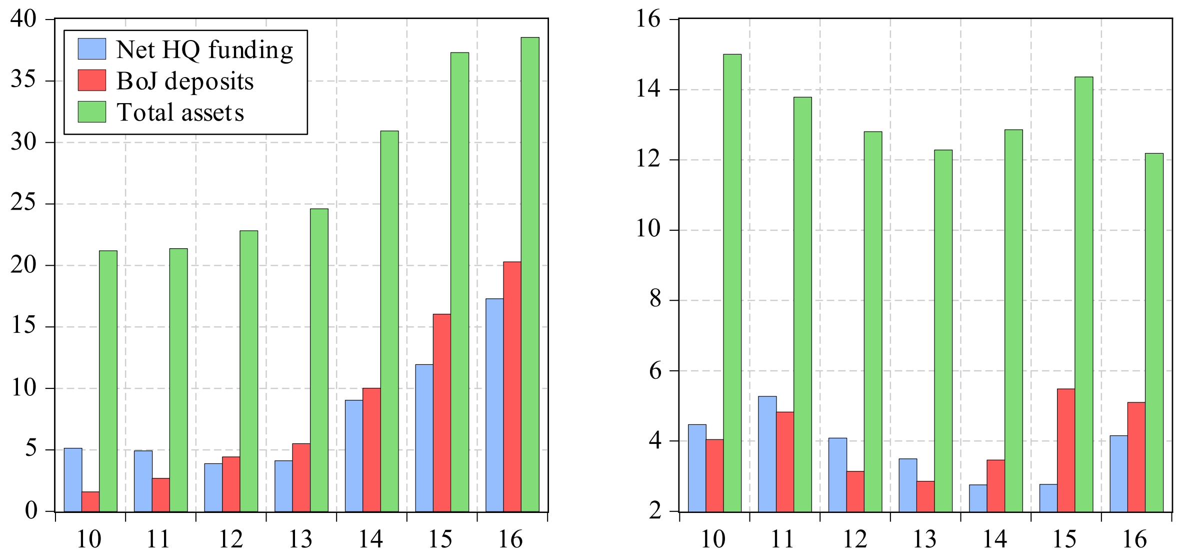
Notes: The Figure characterizes FX swap market equilibrium, by illustrating the link between various types of interest rate differentials, swap-rates, and the direction of swap flows. Vertical lines indicate the level of interest rates in the two countries, exemplified by the "U.S." (left) and "Foreign" (right). The curve connecting the two countries' interest rates is FX swap-implied interest rate differential (in short, the "swap-rate"), while arrows along the swap-rate curve indicate the direction of flows on the "spot-leg" of the swap. Since all market participants face the same swap-rate, these are shifted vertically. A red swap-line marked with zeros means that there are no LOOP deviations (Panel a). Solid lines are market rates, whereas the dashed line represents a hypothetical rate. The black swap-line suggest a profitable opportunity, and arrows show the direction of swap-flows (Panels b-c). Arrows from U.S. means a profitable opportunity by directly raising dollars in U.S. funding markets, while the other direction indicates a profitable opportunity by borrowing in the foreign money market. In Panel (d), the arrows from U.S. indicate a CIP-arbitrage 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 5
Dispersion in USD funding costs for top-rated banks (CD rates)



Notes: The Figure shows the dispersion in funding costs at issuance of 3-month USD Certificates of Deposits (CD) for top-rated banks (A-1/P-1) around the globe. All CDs are represented by dots for days with at least one issue between January 1, 2012 and December 31, 2015. The blue dots represent the average borrowing cost for Asian banks (except banks domiciled in Japan), while the red dots depict CD issuance by banks domiciled in the rest of the world. The black line shows a time series of the USD borrowing cost such that the euro interest rate (after swapping the USD funds obtained via CD issuance into EUR) equals that of the remuneration of ECB's deposit facility. It can be thought of as a break-even rate for the cross-currency arbitrage involving CDs, FX swaps and central bank deposit facilities to be viable. In the same vein, the green line shows a time series of the USD borrowing cost such that the interest rate in yen (after swapping the USD funds obtained via CD issuance into JPY) equals the rate of remuneration of the deposit facility by the Bank of Japan. A borrowing cost below the black and green line means that the issuer has the possibility to reap arbitrage profits by swapping the USD funds to euro and yen respectively, conditional on having access to a deposit account at the ECB or Bank of Japan.

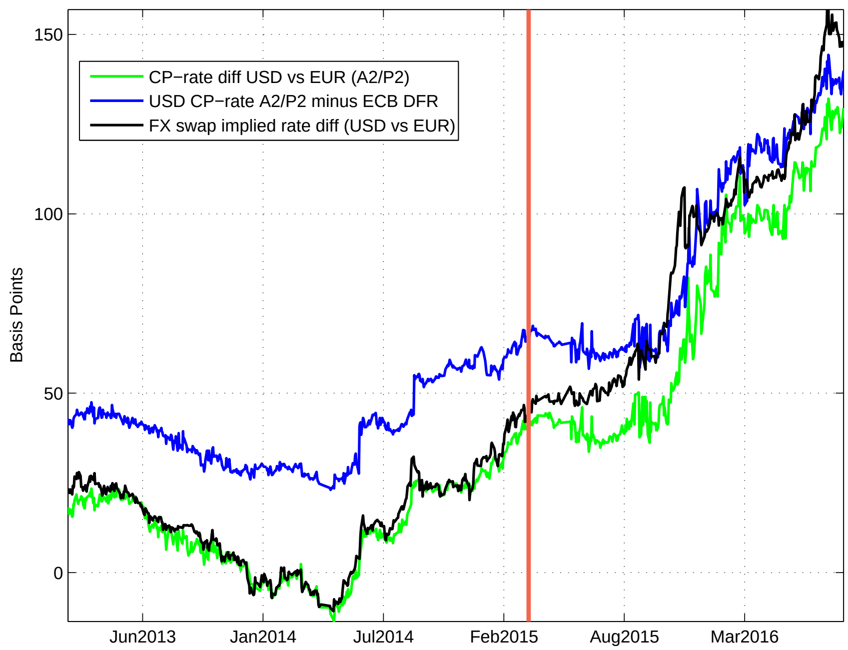
Figure 6
Cash deposits of foreign banks with Bank of Japan



(a) Top rated banks (b) Lower rated banks

Notes: The Figure shows assets, measured in trillions of Japanese yen, of global banks' subsidiaries in Japan, for different rating category. 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 headquarter. Top rated banks (panel a) are rated A-1+/P-1, while Panel (b) is for all other banks. Source: KPMG Japan.

Figure 7
Excess liquidity and USD and EUR money market spreads



Notes: The Figure shows various 3-month interest rate differentials between USD and EUR. The black line depicts the FX swap-implied interest rate differential, whereas the green line shows the difference between the USD CP rate for lower-rated banks (A-2/P-2) and its EUR-denominated counterpart. The blue line shows the difference between the USD CP rate for lower-rated banks (A-2/P-2) and the rate of remuneration on the ECB's deposit facility. The vertical line represents the date when ECB announced its Asset Purchase Program (Jan 22, 2015).

Table 1
Overview of the data

	Tradeable	Risk-free	High-freq	Tenors	Currencies
			A. FX instruments		
Spot (D2)	Y	–	Y	–	AUD, CAD, CHF, EUR, GBP, JPY
FX Swaps	N	–	Y	1W-3M	AUD, CAD, CHF, EUR, GBP, JPY
FX Swaps (D3)	Y	–	Y	1W-3W	AUD, CAD, CHF, EUR, GBP, JPY
			B. Secured money market rates		
OIS	Y	Y	Y	1W-3M	USD, EUR, GBP*, JPY*
			Y	1M-3M	AUD, CAD, CHF
Repo (GC)	Y	Y	D	1M, 3M	USD, EUR
Treasury bills	Y	Y	D	1M, 3M	USD, AUD, CAD, CHF, EUR, GBP, JPY
Central bank deposits	Y	Y	D	1M, 3M	USD, AUD, CAD, CHF, EUR, GBP, JPY
			C. Unsecured money market rates		
Deposit	N	N	Y	1W-3M	USD, AUD, CAD, CHF, EUR, GBP, JPY
IBOR	N	N	D	3M	USD, AUD*, CAD, CHF, EUR, GBP, JPY
Commercial paper	Y	N	D	1M, 3M	USD, AUD, CAD, EUR, GBP, JPY

Notes: The Table shows which of our data satisfy the requirements for realistically implementing a risk-free arbitrage. "Y" is short for "Yes", and "N" for "No". "–" means not relevant or of secondary importance. Tradeable spot and swap rates are from the electronic limit order books Reuters D2000-2 and D2000-3. The maximum range of tenors we study 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 the rest in appendix. The largest set of currencies studied is Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), the euro area (EUR), Great Britain (GBP), and Japansese yen (JPY). All spot and swap rates are against U.S. dollar (USD). An asterisk next to a currency means that not all tenors are available for that currency. Secured interest rates are Overnight Indexed Swaps (OIS), Generalized Collateral (GC) repos, Treasury bills and Central bank deposits. Unsecured interest rates are interbank deposit rates, Interbank Offer Rates (IBOR, survey rates like LIBOR and EURIBOR), and Commercial Paper (CP). Maximum length of samples are beginning of 2005 until December 10, 2015.

Table 2
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 weekend are excluded. Sample: 2005 — December 10, 2015.

Table 3
Comparison of U.S. money market rates

A: Difference to OIS-rate

	Deposits	Repos	IBOR
Mean	0.324	-0.105	0.291
Median	0.174	-0.095	0.145
Maximum	4.776	0.341	3.663
Minimum	-0.140	-1.464	0.025
Std. Dev.	0.478	0.136	0.391
Skewness	4.334	-2.331	3.949
Kurtosis	28.453	16.746	24.023
Observations	2,801	1,740	2,733

B: Correlations

	OIS	Deposit	Repo	IBOR
Levels				
OIS	1			
Deposit	0.961	1		
Repo	0.998	0.958	1	
IBOR	0.975	0.997	0.972	1.00
Changes				
OIS	1			
Deposit	0.071	1		
Repo	0.210	0.113	1	
IBOR	0.265	0.304	0.043	1.00

Notes: The Table compares U.S. 3-month OIS, deposit, GC repo and IBOR interest rates. All rates are measured as ask (offer) rates. Panel A presents descriptive statistics on difference between deposit, repo and IBOR rates and OIS-rates, ie. $i^j - i^{OIS}$, $j \in \{\text{deposit, repo, IBOR}\}$. Panel B presents correlation matrices for all the interest rates, both in levels (B1) and in changes (B2). Maximum length of samples are beginning of 2005 until December 10, 2015.

Table 3
Comparison of EUR money market rates (Cont.)

A: Difference to OIS-rate

	Deposits	Repos	IBOR
Mean	0.259	0.158	0.308
Median	0.104	0.128	0.150
Maximum	2.074	0.894	1.955
Minimum	-0.052	-0.155	-0.016
Std. Dev.	0.335	0.172	0.324
Skewness	2.087	1.747	1.966
Kurtosis	8.061	6.940	7.619
Observations	2,800	2,361	2,763

B: Correlations

	OIS	Deposit	Repo	IBOR
Levels				
OIS	1			
Deposit	0.982	1		
Repo	0.995	0.981	1	
IBOR	0.982	1.000	0.982	1.00
Changes				
OIS	1			
Deposit	0.095	1		
Repo	0.323	0.052	1	
IBOR	0.187	0.265	0.107	1.00

Notes: See previous page.

Table 4
Roundtrip cross-currency basis arbitrage with OIS rates

		GFC and EUR crisis						Post-crisis					
				Deviation						Deviation			
	Direction	Median	Std.	(%D)	(%W)	(%M)	Obs.	Median	Std.	(%D)	(%W)	(%M)	Obs.
AUD	$FCU \Rightarrow USD$	-10.2	40.4	18%	14%	7%	1566	6.9	9.6	64%	61%	56%	717
	$USD \Rightarrow FCU$	2.5	38.2	61%	52%	41%	1566	-12.3	9.5	13%	11%	7%	717
CAD	$FCU \Rightarrow USD$	-13.0	37.3	1%	0%	0%	1566	-7.7	4.0	1%	0%	0%	725
	$USD \Rightarrow FCU$	6.0	31.2	88%	79%	62%	1566	2.4	3.8	76%	67%	47%	725
CHF	$FCU \Rightarrow USD$	-41.3	31.4	0%	0%	0%	1076	-31.2	28.3	0%	0%	0%	718
	$USD \Rightarrow FCU$	32.3	27.9	100%	100%	98%	1076	23.9	24.8	100%	100%	100%	718
EUR	$FCU \Rightarrow USD$	-29.8	38.2	0%	0%	0%	1566	-18.8	16.0	0%	0%	0%	728
	$USD \Rightarrow FCU$	23.5	35.4	92%	91%	88%	1566	12.8	9.3	94%	92%	87%	728
GBP	$FCU \Rightarrow USD$	-13.6	34.7	3%	2%	0%	1395	-8.1	3.7	0%	0%	0%	725
	$USD \Rightarrow FCU$	7.5	31.3	87%	79%	61%	1395	3.1	3.6	99%	97%	95%	725
JPY	$FCU \Rightarrow USD$	-31.1	16.6	0%	0%	0%	796	-23.8	14.4	0%	0%	0%	694
	$USD \Rightarrow FCU$	25.7	16.7	100%	99%	97%	796	19.9	14.2	100%	100%	100%	694

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. Column "Direction" indicates if the round-trip 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 for column "Ave.Dev" implies that a round-trip trade would have been profitable if OIS rates would adequately capture the arbitrageurs' funding costs and the rate at which the swapped funds can placed. "Std.dev" and "% Days" is standard deviation and percentage share of daily observations where positive deviation was observed. Deviation (%D) indicates the fraction of days in the sample a roundtrip deviation exists. Deviation (%W) / (%M) measures the fraction of times a roundtrip deviation can be observed over 5 / 22 consecutive trading days. We report results for two sample periods, "GFC and EUR crisis" Jan 2007 – Dec 2012, and "Post-crisis" Jan 2013 – Dec 10, 2015.

Table 5
LOOP violations with IBOR and interbank deposits

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

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

		GFC and EUR crisis						Post-crisis					
				Deviation						Deviation			
		Median	Std.	(%D)	(%W)	(%M)	Obs.	Median	Std.	(%D)	(%W)	(%M)	Obs.
						A. IBOR							
AUD	(i)	**-12.4**	25.1	10%	5%	1%	1227	–	–	–	–	–	–
	(ii)	**9.6**	19.6	84%	75%	57%	1227	–	–	–	–	–	–
CAD	(i)	**-11.4**	19.1	12%	5%	1%	1500	–	–	–	–	–	–
	(ii)	**7.4**	15.2	77%	67%	51%	1500	–	–	–	–	–	–
CHF	(i)	**-22.5**	25.9	11%	5%	0%	1500	**-15.3**	17.9	0%	0%	0%	729
	(ii)	**19.9**	24.0	81%	74%	62%	1500	**12.4**	15.5	100%	100%	100%	729
EUR	(i)	**-33.7**	33.3	11%	8%	3%	1422	**-13.7**	9.1	1%	0%	0%	711
	(ii)	**31.6**	31.4	88%	85%	77%	1422	**12.4**	8.8	98%	97%	90%	711
GBP	(i)	**-17.0**	30.3	5%	1%	0%	1422	**-2.1**	4.1	12%	7%	1%	711
	(ii)	**15.3**	27.4	91%	85%	76%	1422	**1.4**	4.0	80%	71%	53%	711
JPY	(i)	**-18.5**	20.1	11%	6%	2%	1500	**-15.4**	12.9	0%	0%	0%	729
	(ii)	**16.2**	19.0	84%	77%	68%	1500	**14.3**	12.6	100%	100%	100%	729
						B. Deposit							
AUD	(i)	**-1.1**	6.0	30%	9%	0%	1457	**-1.0**	1.5	8%	0%	0%	717
	(ii)	**0.2**	6.2	53%	29%	14%	1457	**0.6**	1.4	82%	53%	19%	717
CAD	(i)	**-1.5**	4.9	28%	6%	0%	1475	**-0.7**	1.9	21%	1%	0%	725
	(ii)	**0.6**	5.4	58%	26%	3%	1475	**0.3**	1.9	64%	29%	8%	725
CHF	(i)	**-3.8**	6.3	11%	2%	0%	1465	**-2.0**	2.9	2%	0%	0%	718
	(ii)	**2.6**	6.0	71%	54%	32%	1465	**1.3**	2.4	90%	73%	43%	718
EUR	(i)	**-4.0**	9.9	11%	1%	0%	1488	**-0.8**	2.4	13%	0%	0%	728
	(ii)	**3.2**	9.9	81%	62%	40%	1488	**0.4**	2.4	75%	44%	17%	728
GBP	(i)	**-4.5**	7.7	21%	8%	4%	1472	**-0.8**	2.9	26%	5%	0%	725
	(ii)	**3.7**	7.2	74%	53%	32%	1472	**0.6**	2.9	65%	33%	8%	725
JPY	(i)	**-2.0**	4.7	23%	8%	1%	1417	**-2.5**	3.1	10%	0%	0%	694
	(ii)	**1.4**	4.9	68%	43%	22%	1417	**2.3**	3.0	87%	65%	38%	694

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. Deviation (%W) / (%M) measures the fraction of times a LOOP deviation can be observed over 5 / 22 consecutive trading days. Panel A shows calculations using IBOR-rates, while Panel B is based on interbank deposit rates. Sample: 2005 – December 10, 2015.

Table 6
LOOP violations in commercial paper markets

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

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

				Deviation			
		Median	Std.	(%D)	(%W)	(%M)	Obs.
		Panel A: Best-rated banks (A-1+/P-1)					
EUR	(i)	**1.3**	3.5	66%	48%	21%	705
	(ii)	**-2.0**	3.6	26%	15%	10%	705
GBP	(i)	**2.1**	2.5	90%	76%	49%	708
	(ii)	**-2.8**	2.6	5%	2%	0%	708
JPY	(i)	**2.9**	3.6	92%	80%	50%	707
	(ii)	**-4.2**	3.9	3%	0%	0%	707
		Panel B: Top-rated banks (A-1/P-1)					
EUR	(i)	**-7.0**	7.3	9%	3%	0%	715
	(ii)	**6.1**	7.1	88%	82%	73%	715
GBP	(i)	**-2.7**	3.4	5%	1%	0%	716
	(ii)	**2.0**	3.4	84%	69%	44%	716
JPY	(i)	**-3.3**	3.9	22%	9%	1%	716
	(ii)	**2.1**	4.0	69%	62%	54%	716
		Panel C: Lower-rated banks (A-2/P-2)					
EUR	(i)	**-4.2**	8.6	3%	0%	0%	716
	(ii)	**3.4**	8.4	93%	79%	54%	716
GBP	(i)	**-0.3**	4.2	44%	22%	8%	716
	(ii)	**-0.4**	4.1	43%	21%	7%	716
JPY	(i)	**-1.6**	6.4	25%	4%	0%	714
	(ii)	**0.3**	6.1	55%	28%	8%	714

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 LOOP deviation exists. Deviation (%W) / (%M) measures the fraction of times a LOOP deviation can be observed over 5 / 22 consecutive trading days. Panel A show calculations using commercial paper rates of the set of best-rated banks (A-1+/P-1), Panel B uses CP rates for top-rated banks (A-1/P-1), while Panel C reports LOOP violations for lower-rated banks (A-2/P-2). The sample covers the post-crisis period (Jan 2013 – Dec 10, 2015).

Table 7
CIP arbitrage funded via the CP market and investing in T-Bills

	Median	Std.	Deviation (%D)	(%W)	(%M)	Obs.
			Panel A: Best-rated banks (A-1+/P-1)			
AUD	**-21.0**	13.4	18%	11%	0%	161
CAD	**-9.3**	5	5%	2%	0%	683
CHF	**6.0**	10.6	78%	65%	45%	671
EUR	**-3.4**	7.4	32%	23%	14%	705
GBP	**-6.5**	6.7	21%	13%	5%	680
JPY	**12.5**	10.7	100%	100%	100%	492
			Panel B: Top-rated banks (A-1/P-1)			
AUD	**-25.9**	13.2	0%	0%	0%	167
CAD	**-15.5**	5.5	1%	0%	0%	691
CHF	**-0.2**	10.7	49%	28%	9%	679
EUR	**-9.3**	7.4	6%	3%	0%	713
GBP	**-12.5**	6.7	7%	6%	3%	688
JPY	**6.3**	10.6	95%	88%	80%	497
			Panel C: Lower-rated banks (A-2/P-2)			
AUD	**-38.9**	10.4	0%	0%	0%	167
CAD	**-28.6**	6.9	0%	0%	0%	691
CHF	**-13.6**	10.7	9%	6%	3%	679
EUR	**-23.2**	6.1	1%	0%	0%	713
GBP	**-25.3**	7.1	0%	0%	0%	688
JPY	**-4.8**	10.8	30%	18%	9%	497

Notes: The Table shows CIP deviations, measured in basis points, for an implementable strategy involving borrowing in U.S. market. Positive numbers represent arbitrage profits. The bank can fund the trade either in the lower-rated (A-2/P-2) Commercial Paper (CP) rate, Top (A-1/P-1) CP rate, or Best (A-1+/P-1) CP rate. The crucial aspect for a proper arbitrage, seen from the arbitrageur, is that the investment is risk-free, here represented by investing in a government T-Bill. Columns give average CIP deviation, standard deviation of CIP deviations, and share of days it is observed positive arbitrage. Samples: euro-crisis, January 2011 – December 2012; Post-crisis, January 2013 – December 10, 2015.

Table 8
CIP arbitrage funded via the CP market and involving CB deposit facilities

			Deviation			
	Median	Std.	(%D)	(%W)	(%M)	Obs.
			Panel A: Best-rated banks (A-1+/P-1)			
AUD	**-35.9**	11.3	0%	0%	0%	631
CAD	**-1.5**	5.6	35%	24%	12%	688
CHF	**18.7**	18.1	100%	99%	97%	691
EUR	**-3.6**	12.9	44%	42%	37%	688
GBP	**7.4**	3.7	98%	96%	92%	690
JPY	**18.8**	14.8	100%	100%	100%	691
			Panel B: Top-rated banks (A-1/P-1)			
AUD	**-42.6**	11.4	0%	0%	0%	639
CAD	**-7.5**	5.6	14%	9%	2%	696
CHF	**13.1**	17.9	100%	99%	97%	699
EUR	**-9.7**	13.1	29%	25%	19%	696
GBP	**0.6**	3.5	59%	46%	28%	698
JPY	**13.3**	14.6	100%	100%	100%	699
			Panel C: Lower-rated banks (A-2/P-2)			
AUD	**-53.5**	11	0%	0%	0%	639
CAD	**-20.1**	6.9	0%	0%	0%	696
CHF	**0.5**	16.9	53%	41%	31%	699
EUR	**-22.9**	11.5	7%	4%	1%	696
GBP	**-12.9**	5.2	1%	0%	0%	698
JPY	**4.0**	14.8	65%	60%	49%	699

Notes: The Table shows CIP deviations, measured in basis points, for an implementable strategy involving borrowing in U.S. market. Positive numbers represent arbitrage profits. The bank can fund the trade either in the lower-rated (A-2/P-2) Commercial Paper (CP) rate, top (A-1/P-1) CP rate, or best (A-1+/P-1) CP rate. The crucial aspect for a proper arbitrage, seen from the arbitrageur, is that the investment is risk-free, here represented by placing the swapped funds in central bank's deposit facilities. Columns give average CIP deviation, standard deviation of CIP deviations, and share of days it is observed positive arbitrage. Samples: euro-crisis, January 2011 – December 2012; Post-crisis, January 2013 – December 10, 2015.

Table 9
Assets of banks in different rating categories

	Rating category			
	A-1+/P-1	A-1/P-1	A-2/P-2	Lower/No rating
	A: Advanced economy banks			
Average size	749	861	877	310
Total size	8,990	35,301	14,907	19,519
# banks	12	41	17	63
	B: Asian banks (excluding Japanese banks)			
Average size	301	1,026	473	342
Total size	1,803	11,282	3,311	6,155
# banks	6	11	7	18

Notes: The Table shows statistics on assets of global banks (in billions USD) for four different rating groups. The four rating categories are based on ratings from Moodys and S& P, with A-1+/P-1 as best rating. Since Asian banks suffer worse funding costs in U.S. dollar markets, irrespective of the credit rating, we present all non-Asian banks, except Japanese banks, in Panel A, and Asian banks, excluding Japanese banks, in Panel B.

Table 10
Imbalances in the swap market: role of order flow

	A-2/P-2 (1)	A-1/P-1 (2)	A-1/P-1 (3)
Constant	-1.824	-0.848	0.033
	(-2.849)	(-3.016)	(0.192)
Deviation, level lagged	-0.044	-0.067	-0.072
	(-2.313)	(-4.617)	(-6.689)
Swap OF, both dev			2.749
			(2.700)
Swap OF, dev	3.261	0.745	0.649
	(3.085)	(2.450)	(4.425)
Swap OF, no dev	0.910	0.493	0.256
	(2.874)	(2.408)	(1.966)
Liq-premia diff, dev	0.056	0.091	0.040
	(2.538)	(3.095)	(3.373)
Liq-premia diff, no dev	-0.012	-0.157	-0.070
	(-0.560)	(-2.822)	(-4.994)
Spot return, dev	1.452	-0.601	-0.193
	(1.254)	(-1.376)	(-0.619)
Spot return, no dev	-0.537	-1.254	-0.889
	(-0.928)	(-2.147)	(-2.865)
Spot OF, dev	-0.097	-0.005	-0.042
	(-0.373)	(-0.032)	(-0.512)
Spot OF, no dev	-0.211	-0.271	-0.011
	(-1.405)	(-2.224)	(-0.114)
Obs.	1,143	2,598	1,237
adj.R2	0.030	0.096	0.074

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 top-rated banks with A-1/P-1-rating, and invested in central bank deposits. The constant 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. In columns (1) and (2), the cases refer only to deviations for own rating group, e.g. A-2/P-2-based deviation in column (1). In column (3), the effect of swap order flow is split in three cases: Both the CIP condition for top and low-rated banks are in deviation, only that for top-rated banks is in deviation, and none are in deviation. The return on FX spot of the currency, and the liquidity premia differential are measured in basis points, while swap and FX spot order flows are standardized. Sample: Oct 2009 – Dec 2015.

Supplementary Internet Appendix to accompany

Segmented Money Markets and Covered Interest Parity Arbitrage

A. Equations for LOOP and CIP calculations

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

$$1 + i_d = \frac{1}{S}(1 + i_f) F, \tag{OA.1}$$

where i_d and i_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 if it is from the perspective of domestic borrowing, in which case you buy spot and sell forward, or vice versa in the case of foreign borrowing. LOOP of is a weaker condition than CIP (Akram, Rime, and Sarno, 2009).

A. *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,

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

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

where the arbitrage superscript comes from the superscript on the forward part of the swap (i.e, Dev^a in the case of USDJPY means buying USD at the forward leg).[51]

[51] 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.

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

$$
\begin{aligned}
\overline{F^b - S^a}\frac{1+i_f^b}{S^a} &> i_d^a - i_f^b \\
\overline{F^b - S^a}\frac{1+i_f^b}{S^a} + 1 + i_f^b - 1 &> i_d^a \\
\frac{\overline{F^b - S^a}}{S^a}\left(1+i_f^b\right) + \frac{S^a}{S^a}\left(1+i_f^b\right) - 1 &> i_d^a \\
\left[\frac{S^a + \overline{F^b - S^a}}{S^a}\right]\left(1+i_f^b\right) - 1 &> i_d^a
\end{aligned}
\tag{OA.6}
$$

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

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

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

B. LOOP: One-way arbitrage

The law of one price can be violated either for borrowing rates (ask) or lending rates (bid). This is not arbitrage as such because 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:

$$
\begin{aligned}
Ask &: \; 1 + i_d^a \le \frac{1}{S^b}\left(1+i_f^a\right)F^a \\
Bid &: \; 1 + i_f^a \le S^a\left(1+i_d^a\right)\frac{1}{F^b}
\end{aligned}
$$

The first condition says that it is cheaper to finance in domestic market than to swap abroad, while the second state the same from the perspective of the foreign market.

Expressed with swaps, these conditions become:

$$
\begin{aligned}
Ask &: \frac{i_d^a - i_f^a}{1+i_f^a}S^b \le \overline{F^a - S^b} \\
Bid &: \overline{F^b - S^a} \le S^a\frac{i_d^a - i_f^a}{1+i_f^a}
\end{aligned}
\tag{OA.9}
$$

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

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

For the bid side:

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

C. Adding market conventions

There are several issues that have to be taken care of when such conditions as stated above are used calculations using 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 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 ones above must therefore be replaced by 100.

3. Interest rates are quoted as annual rates, and not for the time-horizon of the maturity. 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:

$$Basis_{CIP}^b = -i_d^a + \left[\left(\frac{S^a + \overline{F^b - S^a}/10^4}{S^a} \right) \left(100 + i_f^b \frac{D}{360}\right) - 100 \right] \frac{360}{D}. \tag{OA.12}$$

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 for why OIS based CIP deviations do not reflect risk-less arbitrage opportunities are 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.

As mentioned in the main text (Section II), implementing a CIP arbitrage trade based on OIS contracts is fairly complicated (illustrated by A.3). 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 A.5 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.[52] 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.[53] For example, the effective Fed Funds rate which 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) which can transact in the Fed Funds market, but do not have access to the Fed's deposit facility (Bech and Klee, 2011). The Fed Funds market may

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

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

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 A.4 about here]

Figure A.4 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 points (i)-(ii) above can be quite material in discouraging OIS-based CIP arbitrage.[54]

[Insert Table A.I about here]

In Table A.I we illustrate how potential rollover risk and volatility are related to movements in the EURUSD cross-currency basis calculated from OIS rates. When we filter out the effect of our proxy for roll-over cost and volatility, we see that the average CIP deviation is negative (non-profitable).

[54]The GFC is a primary example of a situation 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.

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 A.5 illustrates the mechanism of using the repo market in CIP arbitrage.

[Insert Figure A.5 about here]

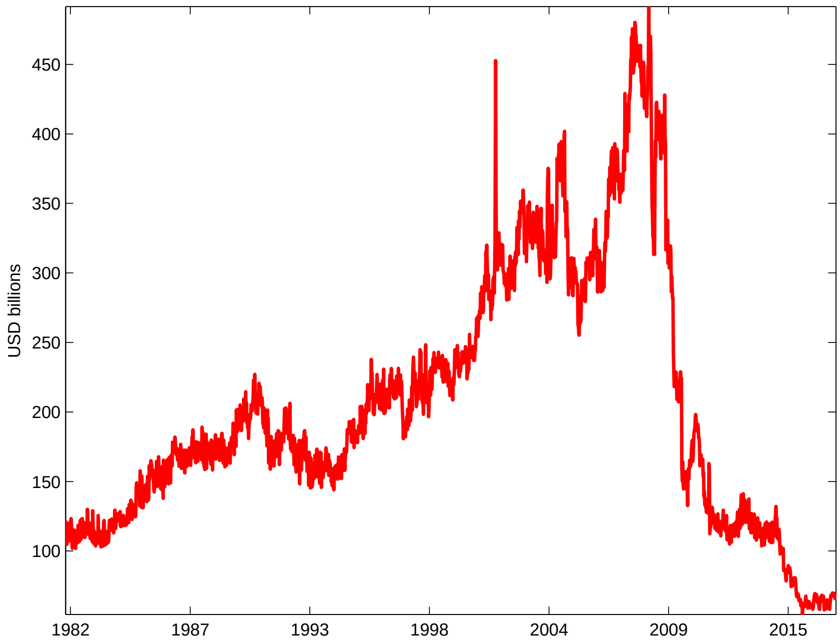
The following example may shed further light on our argumentation in the text that CIP deviations based on GC repo rates reflect cross-currency differences in the total costs of funding the collateral. Depict a bank with an initial portfolio endowment of both US and German Treasuries. These assets are 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 the potential interest rate risk, but cannot generate any more cash during the term of the repo. The bank conducts an FX-swap, receives euro and engages in a reverse repo, receiving German Bunds. The bank can now raise cash in euro 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 thus 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 to compare "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 top-tier 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.

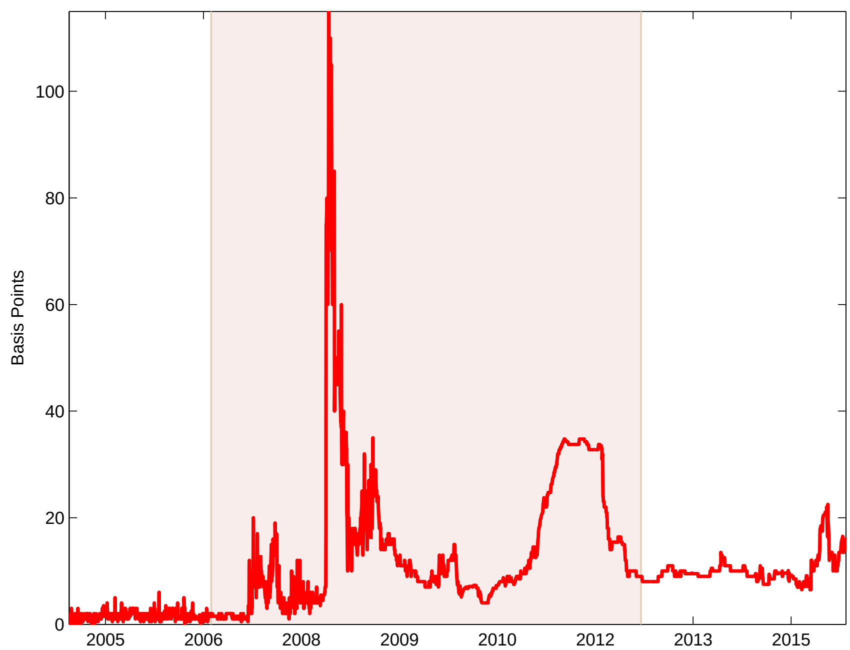
Rehypotecation. There may be situations, however, where market participants are able to use collateral were their own unsecured funding cost is not the correct measure of the full marginal cost. This applies for example to custodians and a practice called rehypothecation. Rehypotecation means that the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

Figure A.1
Activity in US interbank markets



Notes: The Figure shows the evolution of volumes in US interbank markets. The data are taken from the St. Louis Fed FRED database and represent interbank loans comprising all commercial banks, at a weekly frequency. The sample period is from January 1982 until April 2017.

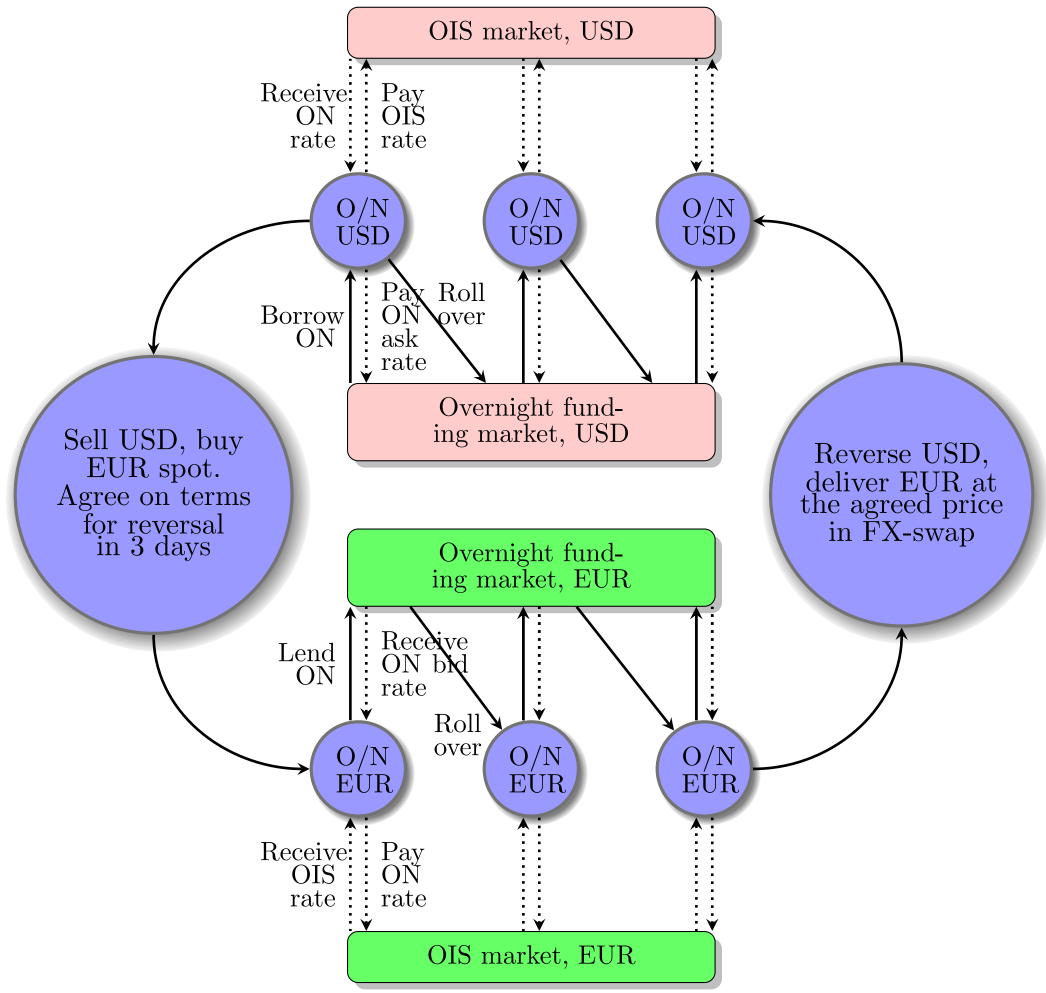
Figure A.2
US dollar funding cost dispersion



(a)

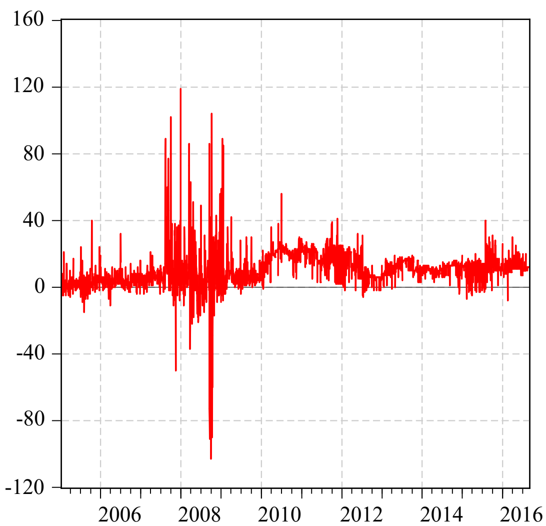
Notes: The Figure shows the range of banks' submissions to the USD LIBOR panel.

Figure A.3
Using OIS contracts in CIP arbitrage

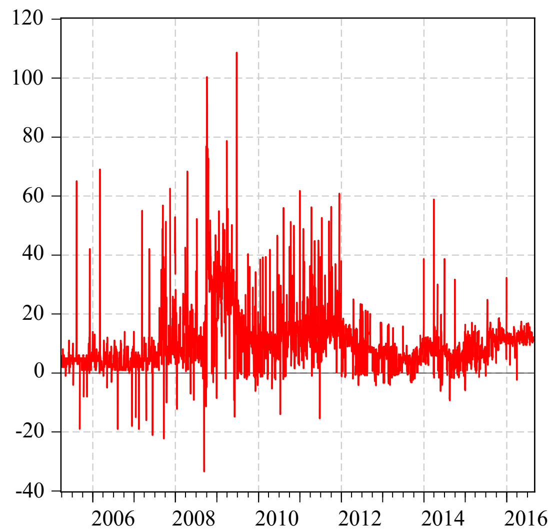


Notes: The Graph shows the mechanics involved in using OIS contracts for CIP arbitrage. Solid lines represent transactions while dashed lines are interest rate payments. In the OIS, the fixed rate is not paid or received every day. It is a fixed rate where the net difference between the average of the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

Figure A.4
Roll-over risk in OIS-based CIP arbitrage



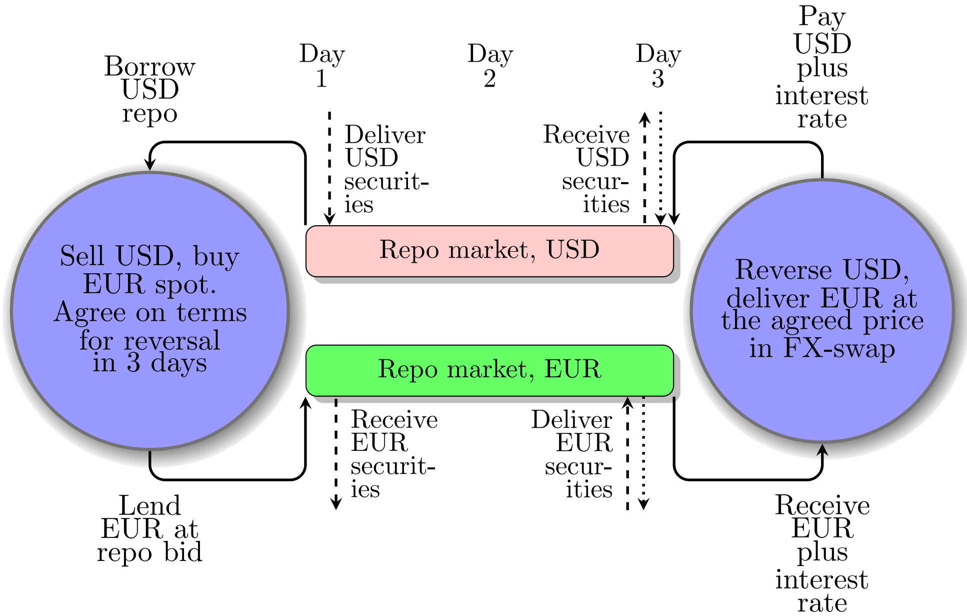
(a) USD



(b) EUR

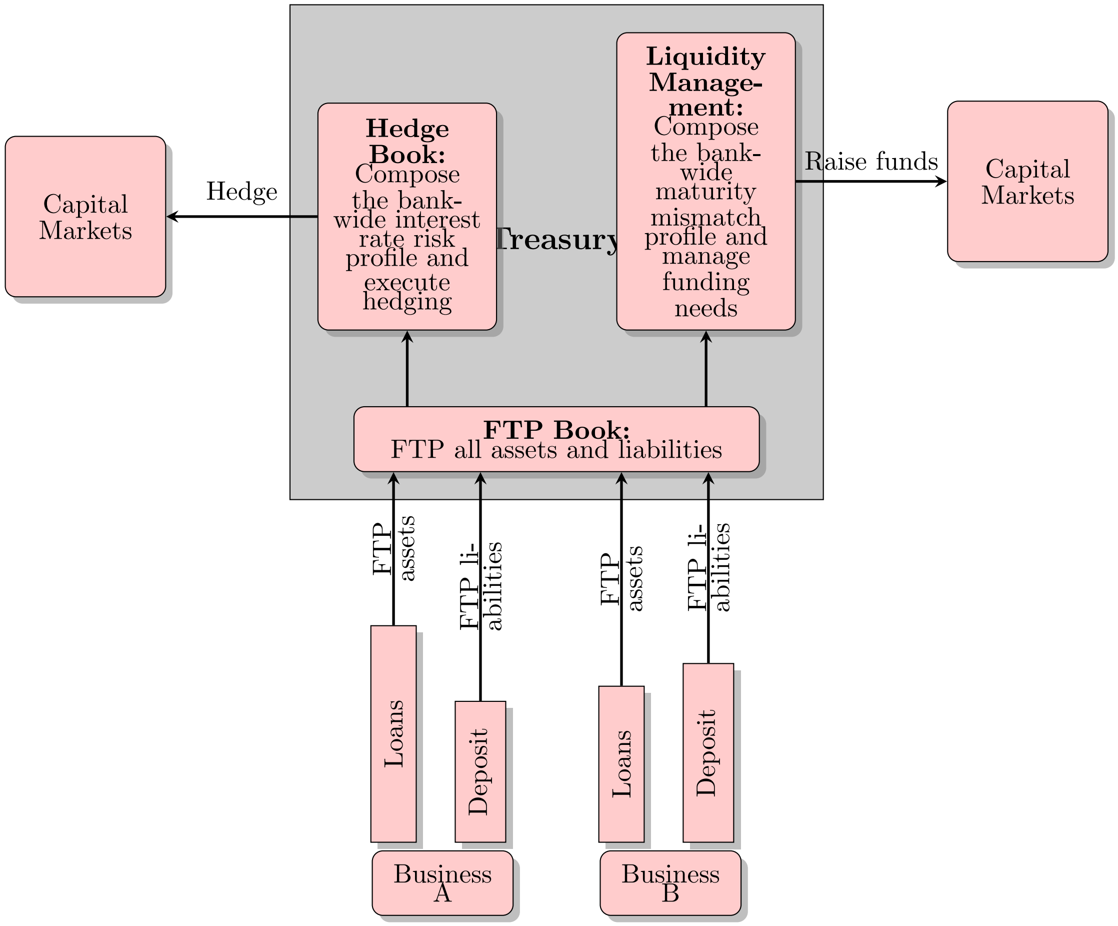
Notes: The Graphs show difference between overnight rates and the underlying overnight rate in the OIS contract measured in basis points. For USD the underlying rate is the Fed Funds rate, while for EUR it is the EONIA-rate. Graphs show the case with borrowing in USD (overnight ask rate minus Fed funds)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

Figure A.5
Using repo contracts in CIP arbitrage



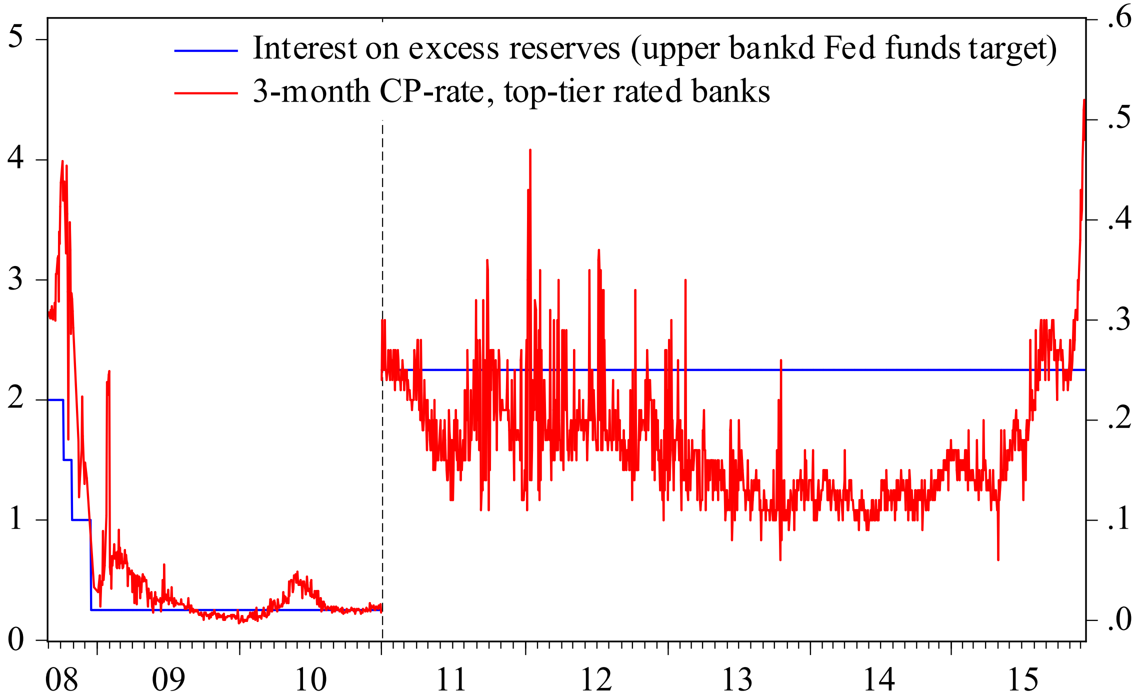
Notes: The Figure shows the mechanics involved in using repo contracts for CIP arbitrage. Solid lines represent transactions while dashed lines depict interest rate payments/security transfers.

Figure A.6
Fund Transfer Pricing (FTP)



Notes: Figure shows the principle of Fund Transfer Pricing (FTP). Source: Tumasyan (2016).

Figure A.7
Funding costs for top-rated banks and interest on excess reserves



Notes: The Figure shows the 3-month CP-rate for top-rated banks together with the interest on excess reserves at the Fed. The Graph is split in two distinct phases, indicated by the vertical dotted line, in order to increase readability.

Table A.I
Roll-over risk in OIS-based CIP arbitrage

	Pre	GFC	EUR	Post	09H1-15H2
Rollover-cost	0.024	-0.112	0.252	-0.042	0.491
	(1.618)	(-2.731)**	(1.537)	(-0.831)	(3.596)**
Volatility of	0.045	0.014	1.382	0.456	1.641
Rollover cost	(1.140)	(0.124)	(1.311)	(2.144)*	(2.946)**
Const.	-0.081	-0.089	-0.035	-0.109	-0.217
	(-24.133)**	(-5.357)**	(-0.401)	(-9.507)**	(-5.117)**
R^2	0.020	0.048	0.039	0.016	0.135

Notes: The Table shows the results from regressing 3-month EUR CIP deviations (measured in percentage points) on OIS transaction costs. These are calculated by $\left(i^{ask}_{ON,USD} - i_{FF}\right) + \left(i_{EONIA} - i^{bid}_{ON,EUR}\right)$, and the moving standard deviation of the transaction cost. Robust t-statistics are reported below coefficients in parentheses. Results are reported for five different sub-samples: "Pre" is Jan 2005–Dec 2006; GFC is Jan 2007– Dec 2009; EUR is Jan 2010– Dec 2012; Post is Jan 2013 — Dec 10, 2015.

Table A.II
CIP arbitrage funded via interbank borrowing

	GFC and EUR crisis						Post-crisis					
			Deviation						Deviation			
	Median	Std.	(%D)	(%W)	(%M)	Obs.	Median	Std.	(%D)	(%W)	(%M)	Obs.
						A: IBOR / T-Bill						
AUD	**3.8**	19.7	63%	50%	28%	1221	**-6.1**	4.9	8%	3%	0%	609
CAD	**-26.4**	33.1	0%	0%	0%	1457	**-17.2**	5.8	1%	0%	0%	726
CHF	**14.8**	24.9	75%	65%	51%	1471	**-2.5**	11.2	38%	19%	5%	719
EUR	**-18.1**	41.2	9%	3%	1%	1403	**-8.9**	8.2	6%	4%	2%	676
GBP	**-10.7**	25.1	18%	13%	6%	1416	**-11.1**	5.5	6%	4%	1%	721
JPY	**0.4**	25.0	50%	47%	38%	1363	**5.0**	11.4	88%	80%	67%	471
						B: IBOR / CP deposit facility						
AUD	**-46.0**	22.4	2%	1%	0%	1125	**-44.9**	10.5	0%	0%	0%	556
CAD	**-17.6**	17.8	6%	3%	0%	1483	**-9.7**	6.1	12%	6%	1%	739
CHF	**-6.2**	123.2	34%	28%	19%	1500	**10.6**	18.2	99%	97%	90%	742
EUR	**-38.0**	61.9	18%	13%	7%	1422	**-12.5**	13.7	20%	14%	7%	722
GBP	**-20.0**	25.6	16%	11%	5%	1420	**-1.5**	3.5	25%	20%	12%	722
JPY	**4.2**	24.6	67%	64%	52%	1035	**10.3**	15.4	99%	96%	90%	742
						C: Interbank deposit / T-Bill						
AUD	**-7.9**	31.0	29%	11%	4%	1229	**-18.4**	11.4	1%	0%	0%	612
CAD	**-45.3**	42.7	0%	0%	0%	1481	**-28.5**	9.2	0%	0%	0%	735
CHF	**-1.7**	26.3	47%	21%	6%	1493	**-13.6**	9.5	7%	0%	0%	726
EUR	**-49.5**	52.6	0%	0%	0%	1428	**-27.7**	9.5	0%	0%	0%	713
GBP	**-27.5**	37.3	2%	0%	0%	1416	**-22.3**	8.2	1%	0%	0%	721
JPY	**-3.9**	17.7	43%	19%	6%	466	**-4.3**	10.1	30%	8%	0%	708
						D: Interbank deposit / CB deposit facility						
AUD	**-61.1**	28.1	0%	0%	0%	1135	**-56.0**	15.8	0%	0%	0%	560
CAD	**-31.8**	30.8	3%	1%	0%	1506	**-21.0**	9.2	1%	0%	0%	752
CHF	**-27.3**	122.6	21%	15%	8%	1539	**1.0**	16.2	55%	28%	11%	756
EUR	**-71.5**	62.2	7%	2%	0%	1439	**-23.0**	10.8	3%	0%	0%	729
GBP	**-32.1**	31.2	4%	1%	0%	1428	**-13.6**	9.7	3%	0%	0%	729
JPY	**-10.0**	38.6	28%	11%	3%	1060	**3.0**	12.5	63%	43%	26%	756

Notes: The Table shows CIP deviations, measured in basis points, for an implementable strategy involving borrowing in USD unsecured interbank funding market.Two risk-free investment assets are considered (government T-Bills and central bank deposit facilities). We report median CIP deviations (positive numbers indicate arbitrage profits) and their standard deviation. Deviation (%D) indicates the fraction of days in the sample a CIP deviation exists. Deviation (%W) / (%M) measures the fraction of times a CIP deviation can be observed over 5 / 22 consecutive trading days.

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