Covered interest rate parity, relative funding liquidity and cross-currency repos

Daniel Kohler*
Swiss National Bank

Benjamin Müller†
Swiss National Bank

May 8, 2018

Abstract

This paper shows that deviations from the covered interest rate parity (CIP), referred to as "FX basis", are considerably smaller when calculated based on so-called cross-currency repo rates instead of standard interest rates such as overnight indexed swap rates or London Interbank Offered Rates. We attribute this finding to the nearly identical risk characteristics of foreign exchange swaps and cross-currency repos: both are virtually devoid of counterparty credit risk but incorporate relative funding liquidity risk. As a consequence, CIP deviations can be exploited on a truly risk-less basis using cross-currency repos. We moreover argue that commonly reported violations from CIP, in particular since 2014, are due to the presence of relative funding liquidity risk, which arises due to the market's preference for holding US dollars over most other currencies.

JEL classification: E43, F31, G12, G14, G15.

Keywords: Covered Interest Rate Parity; FX Swap Market; Cross-Currency Repos; Funding Liquidity Premium; US Dollar Funding.

We would like to thank Iñaki Aldasoro, Benjamin Anderegg, Stefan Avdjiev, Adrian Avdyli, Roman Baumann, Darrell Duffie, Egemen Eren, Lucas Marc Fuhrer, Matthias Jüttner, Oliver Gloede, Cathérine Koch, Antoine Martin, Manuel Mayer, Robert McCauley, Patrick McGuire, Thomas Nellen, Angelo Ranaldo, Dagfinn Rime, Florian Seifferer, Andreas Schrimpf, Greg Sutton, Vlad Sushko, Olav Syrstad, Christoph Theis, and Luca Tonizzo for their helpful comments and suggestions. Moreover, we are grateful for comments received from the participants at the BIS Research Seminar, the Buba-OeNB-SNB Research Workshop, the SNB Brown Bag Seminar, and the MMFX SNB Brown Bag Seminar. The views, opinions, findings, and conclusions or recommendations expressed in this paper are strictly those of the author(s). They do not necessarily reflect the views of the Swiss National Bank (SNB). The SNB takes no responsibility for any errors or omissions in, or for the correctness of, the information contained in this paper.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

*Swiss National Bank, Börsenstrasse 15, P.O. Box, 8022 Zurich, Switzerland, daniel.kohler@snb.ch

†Corresponding author. Swiss National Bank, Börsenstrasse 15, P.O. Box, 8022 Zurich, Switzerland, benjamin.mueller@snb.ch

1. Introduction

US dollar funding bears a premium compared to funding in almost all other currencies. In foreign exchange (FX) swap markets this premium is referred to as the "FX basis", which leads to the failure of a key building block in international finance, the covered interest rate parity (CIP). The CIP relationship postulates that the difference between FX spot and FX forward rates is equal in size to the interest rate differential between the currency areas of the FX transaction. Otherwise, investors could exploit deviations without incurring any risks by borrowing in one currency and lending in the other, while covering all currency risks with a foreign exchange (FX) forward contract of equal maturity. While CIP held tightly before the global financial crisis (GFC), it fails for most currencies vis-à-vis the US dollar since. The widening of the "FX basis" since 2014 is particularly puzzling because it occurred in a benign market environment free from turmoil.

We attribute CIP's alleged failure to the choice of interest rates commonly used when putting the parity relationship to test. Using US dollar (USD), euro (EUR) and Swiss franc (CHF) repo rates from the multi-currency SIX Repo and GC Pooling (GCP) Repo markets coupled with FX spot and forward rates from Bloomberg, we find that CIP holds remarkably well. In fact, CIP deviations are significantly smaller when calculated on the basis of SIX Repo or GCP Repo rates compared to calculations based on overnight-index swap (OIS) or London Interbank Offered Rate (LIBOR) rates. This holds for the USDCHF and the EURUSD and for most time periods under consideration. In particular, this is true for calculations running over quarter-ends when others typically report spikes in the FX basis.

We attribute this finding to the fact that OIS rates do not reflect the premium to acquire US dollar funding correctly. LIBOR rates proxy US dollar funding conditions but are unsecured and thus are subject to counterparty risk. The use of standard repo rates for CIP testing purposes as in Du, Tepper, and Verdelhan (2017) is also imperfect because standard repo rates do not reflect the funding conditions in the respective currencies but rather the premium to turn high-quality liquid collateral into cash. This is in contrast to the repo rates considered in this analysis, which are argued to correctly reflect US dollar funding risk.

US dollar repo rates in both, the SIX Repo and the GCP Repo market, are derived from so-called cross-currency (CCY) repos, i.e. repos where the collateral to secure the transaction is non-US dollar-denominated. Similar to an FX swap, a US dollar CCY repo thus allows to borrow US dollar against collateral denominated in foreign currencies. As a matter of fact, CCY repo rates allow to fully replicate an FX swap because the CCY repo investor can use the very same collateral received in a lending transaction to borrow funds in another currency on a truly risk-less basis.

We emphasize that money market instruments used for CIP testing purposes need to reflect funding liquidity risk which we define in accordance with Rime, Schrimpf, and Syrstad (2017) and in analogy with Brunnermeier and Pedersen (2009) as the ease at which funding can be obtained in one currency compared to another. After all, an FX swap involves the temporary exchange of two currencies which is why relative funding conditions across the two currencies affect its price. The findings of this paper are in line with Wong, Leung, and Ng (2016) and Rime et al. (2017) who argue that CIP holds much better when controlling for relative funding liquidity risk. Compared to the procedures described in their papers, we propose a straightforward and elegant way to disentangle relative funding liquidity risk from other risk components on the basis of CCY repo transactions. Our results are also complementary to the findings of Du et al. (2017), Borio, McCauley, McGuire, and Sushko (2016) and Sushko, Borio, McCauley, and McGuire (2016) who attribute the failure of the CIP since 2014 to limitations of arbitrage activity arising from regulation and related balance-sheet restrictions. Regulatory cost and window-dressing factors might exert their market impact via the relative funding liquidity premium and this market impact might be particularly strong at quarter-ends.

As funding cost are reflected in the pricing of financial intermediation services offered by banks and transactions among banks, (relative) funding liquidity risk is expected to translate into further financial market segments. For instance, we argue, that relative funding liquidity risk affects not only the cash market but also collateral markets. That is, investors should not only exhibit a preference for US dollar cash but also for US dollar collateral. To give an example, we conjecture that so-called securities lending and borrowing transactions, involving a temporary exchange of collateral denominated in different currencies should reflect relative funding liquidity risk as well. This finding has important policy implications. For instance, it is widely acknowledged that the central bank US dollar swap line contributed significantly towards alleviating US dollar funding tensions during the Global Financial Crisis. We are of the opinion that it is such a powerful tool because it is setup as a CCY repo where non-US banks can access US dollar funding against collateral that is accepted at their home central bank and which is usually non-US dollar denominated. By this, the US dollar swap line essentially imposes a limit on the size of the relative funding liquidity risk premium. Most likely, the swap lines would be ineffective if US dollar collateral were required to access the facility.

Despite the wide-ranging implications, our paper cannot pinpoint the exact sources of the relative funding liquidity premium. In particular, it is not understood why almost all currencies exhibit such a pronounced relative funding liquidity premium against the US dollar. We can only speculate that the role of the US dollar as the dominant currency in the global funding and settlement markets, linked with highly developed and liquid US financial markets as well as central bank policies, could be an important driver. Moreover, we know that CIP held tightly before the financial crisis and this is irrespective of the interest rate under consideration and the currency pair analyzed. This suggests that the funding liquidity risk premium was essentially zero. In our view, this should be investigated in more detail in future research.

The remainder of this paper is organized as follows. Section 2 embeds our research into the broader literature. Section 3 defines the CIP condition by showing how interest rate differentials are related to a FX swap. Section 4 then zooms in on practical aspects of CIP arbitrage and the associated risks as well as the role of CCY repos. Section 5 sheds light on the institutional details of two CCY repo markets. From these markets, CCY repo data are inferred and this is discussed in Section 6. Section 7 then presents the results of our empirical analysis and Section 8 discusses these results and identifies implications for policymakers and scope for future research. Finally, Section 9 concludes.

2. Literature

The CIP relationship held quite tightly prior to the GFC. Testing the relationship on the basis of contemporaneously sampled high-frequency data recorded on November 11, 12 and 13, 1985, Taylor (1987) found overwhelming support in favor of CIP. Looking at high-frequency data as well, Akram, Rime, and Sarno (2008) report numerous arbitrage opportunities. Violations are, however, shown to be short-lived with profit opportunities dissipating quickly.

Large and persistent deviations only came to the fore during and after the GFC. CIP exhibited extreme dislocations after the failure of Lehman Brothers on September 15, 2008. Several studies investigated these dislocations with the conclusion that the violations were caused by an acute shortage of US dollar liquidity in the interbank market and by heightened counterparty credit risk (see, for instance, Baba, Packer, and Nagano (2008)). According to Coffey, Hrung, and Sarkar (2009), the continuous extension of central bank swap line facilities, which allowed domestic banks to get hold of US dollar liquidity through their home central bank, finally led to an alleviation of these tensions. While deviations from CIP normalized from their extreme levels seen in autumn 2008 towards the beginning of 2009, the parity relationship never returned to pre-crisis levels.

Another sharp spike occurred when the sovereign debt crisis was at its worst towards the end of 2011 and the European banking system found itself with a shortage of US dollar liquidity (see Allen and Moessner (2013)). More recently, the CIP relationship came into the spotlight again as deviations have widened since mid-2014, both for short- and long-term borrowing. Puzzlingly, departure from CIP now happened without there being any obvious sign of market stress.

Several explanations have been brought forward for the CIP breakdown since 2014. Recent studies suggest that arbitrage opportunities remain unexploited due to increased financial regulation. In support of this argument, Du et al. (2017) point to widening deviations towards quarter-end reporting dates. Borio et al. (2016) and Sushko et al. (2016) identify regulation as an important impediment to arbitrage as well. They identify imbalanced FX hedging demand as the main culprit for CIP deviations opening up in the first place.[1] While not negating that regulation might play a certain role, in particular towards quarter-ends, our paper is mostly related to another strand of literature. Along the lines of Baba et al. (2008), Baba and Packer (2009), McGuire and von Peter (2012), Mancini-Griffoli and Ranaldo (2010) and, in particular, recent literature by Rime et al. (2017) and Wong et al. (2016), we argue that CIP actually held if all market risk premia were taken into account properly.

Focusing on the literature explaining CIP deviations since mid-2014, our paper is most related to the following contributions: Rime et al. (2017) stress the large degree of segmentation in money markets and, related to that, the difficulty in choosing the right interest rate when evaluating CIP arbitrage opportunities. They run their analysis on commercial paper rates, which are argued to reflect banks' true marginal funding cost, and find that CIP arbitrage is confined to a relatively small set of highly-rated global banks with access to cheap financing in the US commercial paper market. The large deviations found when using OIS rates are primarily attributed to the existence of funding liquidity risk which OIS rates fail to capture. Using LIBOR-OIS spreads combined with FX swap prices for various currencies, Wong et al. (2016) decompose CIP violations into counterparty credit and funding liquidity risk. They find that funding liquidity risk plays the dominant role in explaining CIP deviations and interpret this as evidence that traders price FX swaps taking into account funding liquidity risk while filtering out counterparty credit risk. Our paper contributes to this discussion by showing a straightforward way to properly disentangle counterparty credit risk from funding liquidity risk.

Our paper is also related to Du et al. (2017) relying on repo rates, among others, in order to test the CIP. Using (indicative) 1W general collateral (GC) repo rates in US dollars, euros,

[1] Related to this, Avdjiev, Du, Koch, and Shin (2016) find evidence for a relationship between the US dollar spot exchange rate and US dollar CIP deviations. The underlying mechanism generating this relationship is argued to be the shadow price of bank leverage which is driven by the value of the US dollar vis-à-vis other currencies. If the US dollar strengthens, it is argued that the banks' risk bearing capacity decreases, which in turn allows for wider CIP deviations.

yen, Danish kroner and Swiss francs from Thomson Reuters and Bloomberg, they report substantial CIP deviations.[2] We claim that the use of conventional (indicative) repo rates for testing CIP is imperfect for two reasons: First, conventional repo rates don't allow a CIP arbitrage strategy to be set up as the collateral received by lending in one currency cannot be re-used to borrow in another currency.[3] Second, we argue that repo rates, in contrast to CCY repo rates, do not incorporate relative funding liquidity risk which is present in FX swap prices.

We also contribute to the empirical literature on the pricing of repo transactions by showing that CCY repo rates incorporate a relative funding liquidity premium. We argue that this price differentiation is somewhat related to the price differentiation of special repos compared to regular GC repos.[4] If the securities involved in a special repo demand a scarcity premium, the special repo rate should deviate from corresponding GC repo rates. In a CCY repo where the cash leg and the collateral leg are denominated in different currencies, such a scarcity premium arises if the market exhibits a preference for one currency over the other. In times of US dollar scarcity, obtaining cash in US dollars against collateral in another currency should, for instance, demand such a premium.

3. Covered interest rate parity

CIP is a key building block in international finance that relates the pricing of an FX swap consisting of a spot (S) and a forward exchange rate (F) to the interest rate differential ($i^p - i^b$) between two currencies. It postulates that the relationship between the forward and the spot exchange rate should be governed exactly by the interest rate differential between the two currencies involved:

$$\frac{F_{t,t+1}}{S_t} = \frac{1 + i^p_{t,t+1}}{1 + i^b_{t,t+1}}. \tag{1}$$

[2]General collateral or GC repos are defined in more detail, below. For now, a GC repo can be regarded as a collateralized funding instrument.

[3]In Du et al. (2017), CIP arbitrage is tested for the US dollar vis-à-vis the currencies mentioned. For arbitrage strategy to be profitable, the arbitrageur needs to borrow US dollars in the repo market and subsequently convert these US dollars into the foreign currency. However, to borrow US dollars in the conventional repo market, the arbitrageur needs US dollar-denominated collateral, usually US Treasuries, in the first place. We claim that all transactions serving to source US dollar assets (here US Treasuries) involve paying the FX basis which should drive alleged CIP deviations to zero (see our discussion in Section 7.2).

[4]While GC repos are driven by acquiring cash, special repos are driven by acquiring specific securities for the length of the repo contract. For instance, special repos are used to short sale securities that involve a specialness fee, i.e. are in short supply (see Duffie (1996) for an overview).

In logarithmic terms, Equation (1) reads:

$$f_{t,t+1} - s_t = i^p_{t,t+1} - i^b_{t,t+1}, \tag{2}$$

where $f_{t,t+1}$ corresponds to the log forward rate at time t for value date at time $t+1$ and s_t is the log spot rate at time t. The interest rate in the country with the price currency is represented by $i^p_{t,t+1}$ while the interest rate in the country of the base currency corresponds to $i^b_{t,t+1}$. The term on the left-hand side of Equation (2) corresponds to the FX swap pricing also referred to as forward rate premium or FX swap points.

Note that all variables in Equation (2) represent instruments whose prices are known with certainty at time t. This makes CIP an arbitrage relationship whose violation opens profit opportunities without incurring any (obvious) risks. To see that more clearly, assume for a moment that Equation (2) failed to hold, such that

$$s_t - f_{t,t+1} + i^p_{t,t+1} - i^b_{t,t+1} > 0. \tag{3}$$

Speculators could now borrow at the money market borrowing rate $i^b_{t,t+1}$ (for instance US dollars), change the cash amount at the spot exchange rate, s_t (for instance sell US dollar against Swiss franc spot), and invest the proceeds in price currency at $i^p_{t,t+1}$ (Swiss franc). To hedge against exchange rate risks during the duration of the transaction, a forward contract could be bought at $f_{t,t+1}$ (buy USDCHF forward).

Equation (3) can be rewritten as follows:

$$s_t - f_{t,t+1} + i^p_{t,t+1} - i^b_{t,t+1} + \epsilon = 0, \tag{4}$$

where ϵ denotes CIP deviations or the FX basis.[5]

In theory, assuming efficient markets, all deviations should be arbitraged away immediately. However, potential arbitrageurs are likely to run into difficulties when looking at practical aspects of measuring and exploiting CIP violations. Due to the segmentation of the money market landscape, there are a variety of potential money market rates that could be plugged into the above equation. These interest rates differ with respect to liquidity and counterparty credit risk characteristics and it is impossible that CIP can hold for all money market rates. Moreover, exploiting CIP violations requires that an arbitrage strategy can

[5]Henceforth, CIP deviations and FX basis are used synonymously.

effectively be constructed. Thus, testing CIP requires careful thinking about the properties of the various money market instruments and we argue that CCY repo rates are appropriate to use, while there are concerns with OIS, LIBOR, or standard (non-CCY) repo rates.

4. Cross-currency repos and CIP arbitrage

A CCY repo only differs from a standard repo transaction (henceforth referred to as conventional repo) in that the cash amount is denominated in a different currency than the collateral transferred. More specifically, instead of securing a US dollar loan with US Treasuries as it is standard in a conventional repo, German or Swiss government bonds would instead be used to secure the US dollar loan in a CCY repo. Otherwise, a CCY repo is identical to a conventional repo: it is a transaction where one party sells securities to another while committing itself to repurchase them at a pre-specified price at some future date; in essence, a collateralized loan. The securities received in conventional as well as CCY repos are typically high-quality, liquid fixed-income securities (usually government bonds). Thus, both are (almost) exempt from counterparty credit risk. The primary motive of conventional and CCY repos is cash lending and borrowing. Thus, the collateral delivered to secure the transaction often plays a subordinate role as long as it is compliant with eligibility criteria. In other words, in contrast to special repos, conventional and CCY repos should not be affected by a collateral premium.[6]

Subsequently, we argue that CCY repo rates are appropriate to test the CIP because CCY repos allow to replicate an FX swap, the exchange of two currencies at a spot and a forward rate, and thus to arbitrage away CIP violations, effectively. Moreover, we argue that CCY repo rates replicate the risk structure of an FX swap. The two arguments are of course complementary and both imply that the CIP tested based on CCY repo rates should hold more tightly than for other money market rates such as conventional repo rates, OIS rates, or LIBOR rates.

4.1. Arbitrage view

We have claimed previously that CCY repos enable CIP arbitrage on a truly risk-less basis. To see that more clearly assume that the collateral receiver in a CCY repo is allowed to re-use the securities. In fact, this is indeed possible in the case of the CCY repo market analyzed subsequently, where a lender giving a loan in one currency (say in Swiss franc)

[6]Note that in spite of the exchange rate mismatch, a CCY repo transaction is not subject to exchange rate risk. Exchange rate fluctuations might, however, result in frequent re-evaluations and margin calls.

against collateral could re-use the very same collateral to borrow in another currency (say in US dollar).[7] Note that this sequence of transactions perfectly replicates a USDCHF FX swap because the collateral receiver started with Swiss francs and ends up with US dollars for the term of the repo contract. The two transactions leave him without any collateral at all and hence without entitlement to interest or dividend payments or exposure to price fluctuations.[8] Moreover, the investor is also not exposed to a collateral premium, which should be insignificant for GC repos anyway.

Given that this strategy perfectly replicates an FX swap, the pricing should be identical. If not, an arbitrage opportunity would arise, which allows investors to generate a positive return by sourcing cash in one currency using the cheaper strategy and offer cash in the other strategy. Such an arbitrage opportunity should immediately attract speculative flows until the interest rate differential derived from the two CCY repo transactions is aligned to the pricing of the FX swap. Note that arbitrageurs would run into difficulties when trying to set up an arbitrage strategy based on many other money market instruments. For instance, it is impossible to conduct CIP arbitrage based on conventional repos as the collateral received in the first transaction is not eligible to borrow in the second transaction. In order to execute the second transaction (borrowing US dollar), US dollar collateral needs to be acquired first. Funding this collateral comes at a cost which should drive the arbitrage gain towards zero. A combination of OIS transactions does not allow to set up an arbitrage strategy neither, because an OIS is an interest rate swap involving the settlement of the net contract value at the expiry date of the contract, only. CIP arbitrage requires an exchange of notional values at the beginning and at the end of the FX swap transaction (a detailed description of the characteristics of an OIS is provided in Appendix A).

Numerous studies analyze the CIP relationship on the basis of LIBOR, which reflects the interest rate at which prime banks are able to borrow on an unsecured basis and for different maturities.[9] Being unsecured, LIBOR transactions incorporate counterparty credit risk and hence do not qualify for conducting CIP arbitrage. In addition, the representative content of LIBOR is questionable and it cannot be taken for granted that a CIP arbitrage can effectively be set up based on LIBOR rates. This is because LIBOR is based on quotes of the submitting prime banks and because of a general decline in the underlying market of unsecured interbank transactions during and after the GFC. Reports of manipulative

[7] See Fuhrer, Guggenheim, and Schumacher (2016) for an in-depth discussion of the re-use of collateral.

[8] Although he is the beneficial owner of the collateral provided, all proceeds need to be channeled to the borrowing counterparty on the other side of the second transaction.

[9] Strictly speaking, LIBOR represents an indicative ask interest rate, i.e. the rate at which a prime bank could borrow unsecured. When calculating CIP deviations based on LIBOR, the rate is also used for the rate at which the currency received in the FX swap can be invested, i.e. the bid interest rate. In the paper, we follow market practices and use LIBOR as a proxy for general unsecured funding conditions.

behavior add to reservations (a detailed description of the characteristics of the LIBOR is provided in Appendix A).[10]

4.2. Risk view

Another way to reflect on CIP is to think about the risks involved in an FX swap and in money market transactions. Equation (2), which relates FX swap points on the left-hand side to money market interest rate differentials on the right, clarifies our point. For CIP to hold, the pricing and hence risk premiums on both sides of the equation must be the same. We argue that CCY repo differentials match the risk structure of an FX swap, while conventional repo, OIS and LIBOR interest rate differentials usually fail to do so. Of course, these risk considerations are closely related to the arbitrage argument from above because genuine arbitrage is only possible in a system without any residual risks.

To analyze risks, we differentiate between counterparty credit risk and (relative) funding liquidity risk. We define counterparty credit risk as the risk of a debtor defaulting on its contractual obligations. Following Brunnermeier and Pedersen (2009), funding liquidity risk is defined as the ease at which funding can be obtained. The relative funding liquidity risk premium describes the difference in premiums between funding in two different currencies. Note that the funding liquidity premium is very much related to the liquidity characteristics of an asset. An investor demands compensation in terms of a premium for an asset that cannot be converted into cash easily, i.e. which is illiquid. Instead of measuring the liquidity characteristics relative to cash, the relative funding liquidity premium of a currency is measured as the funding liquidity premium relative to a reference currency. We are first investigating risks involved in a FX swap transaction before zooming-in on risks involved in money market rates.

4.2.1. Risks in a FX swap transaction

Assume an investor entering an FX swap transaction by selling the base currency against the price currency in the spot market at s_t (sell USDCHF spot), while simultaneously buying the same amount of the base against the price currency in the forward market at $f_{t,t+1}$ (buy USDCHF forward). Besides the fact that such a position is immune to FX risks because all gains and losses on the spot leg of the transaction are offset by gains and losses of equal size but opposite sign on the forward leg, it does not involve counterparty credit risk. If the

[10] During the GFC some contributors resorted to understating their borrowing costs in order to avoid the perception that their default risk had deteriorated. Others manipulated contributions with the goal of making a profit on derivative positions referencing to the LIBOR. See, for instance, Duffie and Stein (2015).

counterparty were to default, the investor would be left with the price currency as collateral.[11]

At first sight, an FX swap transaction does not involve much funding liquidity risk either. Liquidity is not tied up during the contract's term but merely exchanged for liquidity in another currency. After all, the initial currency can always be procured again, should the need arise, for instance, by re-converting the proceeds into the original currency on the FX spot market. Such a procurement would, however, involve a fair amount of exchange rate risk because at the FX swap contract's maturity, the investor is contractually obliged to return the currency received from its counterpart.[12] To avoid exchange rate risks, the procurement of the original currency could also be achieved by closing the initial position with an FX swap transaction bearing the opposite sign, bearing the same maturity date as the original swap. In our example, the investor would enter a buy and sell USDCHF FX swap transaction. Such a reversal would cost dearly, if at the time of the reversal, US dollar funding conditions deteriorated. In fact, the dislocation of the FX swap market during the GFC is a prime example of how US dollar liquidity suddenly became scarce due to an imbalance in the demand and supply of US dollars in the FX swap market leading to an increase of the US dollar funding liquidity premium relative to the funding liquidity premium of almost all other currencies.

4.2.2. Risks in money market rates

As outlined before, CCY repo differentials can be considered as being secured, because both legs of the transaction are collateralized with high-quality, liquid securities. Thus, such a position is (almost) exempt from counterparty credit risk. The CCY repo investor is however left with relative funding liquidity risk arising from a temporary currency mismatch, just as if he had entered into an FX swap with the same maturity date.

Based on the intuition provided above and elaborated in more detail in Appendix A, OIS rates fail to match the risk structure of an FX swap because there is no exchange of notional values and thus there is no (relative) funding liquidity risk premium incorporated in OIS rates. The lack of exchange of notional values combined with the fact that OIS agreements are usually subject to margin calls, OIS rates incorporate hardly any counterparty credit

[11] Counterparty credit risk exposure could arise from price movements resulting in an unrealized profit on the far leg of the transaction. However, such profits tend to be small in comparison to the notional amount exchanged at the beginning of the contract. Moreover, swap positions are normally subject to marking-to-market procedures resulting in margin calls if profits or losses accrue.

[12] To see that more clearly, assume that an investor had entered, say, an FX swap delivering US dollars against Swiss francs at the near leg. The FX swap contract obliges the investor to return the Swiss franc amount at the maturity date of the swap. If the investor faced a sudden US dollar need during the term of the contract leading him to re-exchange the Swiss franc amount into US dollars in the spot market, he would find himself with a short Swiss franc exposure thereafter.

risk premium.[13]

Finally, unsecured money market rates incorporate funding liquidity risk because liquidity is tied up during the transaction and by borrowing in one currency and lending in the other. Thus, LIBOR interest rate differentials reflect the relative funding liquidity premium. However, LIBOR rates also incorporate a counterparty credit risk premium. Proponents of the LIBOR might argue that the premium is likely to affect domestic as well as foreign interest rates and thus cancels out on the right-hand side of Equation (2). However, the composition of the LIBOR panel differs from currency to currency so that the counterparty credit risk component in the two currencies underlying the FX swap is usually not equal in size.[14]

4.3. Summary

To summarize and as displayed in Table 1, an FX swap involves hardly any counterparty credit risk because it essentially amounts to a collateralized transaction. It comes with a fair amount of relative funding liquidity risk though, which arises due to the exchange of two currencies with different funding liquidity risk premia.

Table 1: Risks associated with CIP arbitrage

Instrument	Rel. counterparty risk	Rel. funding liquidity risk	Arbitrage
FX swap pricing	-	✓	
OIS rate diff.	-	-	-
LIBOR rate diff.	✓	✓	-
Repo rate diff.	-	-	-
CCY repo rate diff.	-	✓	✓

Table 1 displays the risks incorporated in the pricing of FX swaps as well as the money market interest rate differentials for the instruments under consideration. It also displays whether arbitrage is feasible or not. Note that the representation is in relative terms and depicted for instruments with a maturity larger than ON. To give an example, as described above, the relative counterparty and the relative funding liquidity risk is non-zero for OIS. However, it is very small relative to the respective risks incorporated in LIBOR rates. Thus, there is neither a checkmark with OIS rates for the relative counterparty nor the relative funding liquidity risk.

CCY repos allow for CIP arbitrage and reflect the same risk structure as an FX swap

[13]For assigning the different risks to the money market instruments, we implicitly assume that the maturity is longer than ON. Otherwise, OIS rates would need to have the same risk structure as LIBOR rates because OIS rates are usually based on overnight unsecured funding rates that represent the variable leg of the OIS contract.

[14]There is a cross-sectional difference between LIBOR-OIS spreads for different currencies, which is evidence that the relative counterparty credit risk premium is non-zero.

with negligible counterparty credit risk but the presence of relative funding liquidity risk. While unsecured money market transactions, usually approximated by LIBOR rates, can be used to exploit CIP deviations, they are subject to counterparty credit risk and thus do not allow for (risk-free) arbitrage. Setting up a CIP arbitrage strategy based on OIS rates is not feasible because they fail to reflect relative funding liquidity risk. Thus, we expect CIP represented by Equation (2) to hold more tightly than for all other interest rates discussed above. We also expect spikes in the FX swap pricing on quarter-ends documented in the literature to be reflected by CCY repo rate differentials such that CIP deviations calculated based on CCY repo rates should be small within-quarters as well as on quarter-ends. Finally, we expect CIP deviations calculated based on OIS or LIBOR rates to rise with the maturity of the contract, while deviations based on CCY repo rates to remain small. This is because we expect the relative funding liquidity and the counterparty credit risk premium to rise with the term of the contract.

5. Cross-currency repo markets

The CCY repo rates under consideration in our empirical analysis are derived from the multi-currency SIX and the GCP Repo markets and the institutional details of these markets are discussed below.

5.1. Institutional details of the SIX Repo market

The SIX Repo market is the representative secured money market in Switzerland. The major segment is the Swiss franc market, i.e. repos where the cash leg is denominated in Swiss francs. However, other currencies and in particular US dollars can be traded on the platform, too.[15] Trades are concluded on an electronic trading platform with a direct link to the central securities depository (CSD) and to the real-time gross settlement payment (RTGS) system for trades with cash leg in Swiss francs. Trades with non-Swiss franc cash legs are settled via a correspondent bank. Participants are mostly banks domiciled in Switzerland and abroad, some with global reach while others are more focused on domestic markets. Moreover, insurance companies as well as Swiss federal agencies participate in the market.

The SIX Repo market is regarded as a GC repo market. In other words, the main focus of the repo trade is not to acquire specific securities, which would be the case in special

[15]Other currencies include the euro, Canadian dollar, Japanese yen, Australian dollar, New Zealand dollar, Swedish krona, Norwegian krone, Danish krone, Hungarian forint, Czech koruna and Polish zloty. These currencies are summarized as other currencies because they are traded very rarely in comparison to transactions in Swiss francs, US dollars and euros.

repos, but to acquire funding. These types of repo transactions are called GC repos because the collateral exchanged is of second-order relevance as long as it fulfills certain requirements with respect to the credit and liquidity qualities. Securities that fulfill these requirements are summarized in so-called collateral baskets and GC repos are conducted against these collateral baskets whereby the collateral receiver lacks knowledge of the specific securities delivered when accepting a trade.

In the case of the SIX Repo market, the collateral standard used in interbank repo transactions is the same standard that the Swiss National Bank (SNB) uses in its monetary policy operations. Securities that fulfill the SNB eligibility criteria are summarized in the so-called SNB GC basket. Note that this basket is used as the standard, irrespective of the currency of the cash leg. For the period under consideration and in the Swiss franc (US dollar) segment, 91% (97%) of the outstanding volume was collateralized by the SNB GC basket. Securities in the SNB GC basket are high-quality liquid securities that can be denominated in the following currencies: Swiss franc, euro, US dollar, pound sterling, Danish krone, Swedish krona, Norwegian krone. The potential volume of SNB eligible collateral stood at 8,915 billion Swiss francs as of the end of September 4, 2017. About 66% of the potential outstanding volume is denominated in euros, 22% in pounds sterling, 3% in Swiss francs, 3% in Swedish kronor, 3% in Danish kroner, 2% in US dollars and 1% in Norwegian kroner.[16]

The re-use of collateral is permitted and the default case if not explicitly ruled out in the contract specification agreed upon bilaterally. That is, the cash lender can make use of the collateral received in a first transaction to borrow against collateral in a second transaction. Re-use is possible across currency segments. That is, a participant could lend Swiss francs and receive collateral that could be re-used to borrow US dollars by providing exactly the same securities. As the standard in the SIX Repo market is a haircut of zero (no overcollateralization of the cash loan), haircuts do not restrict the re-use activity.

Thanks to data about the specific securities (ISIN-by-ISIN or equivalently CUSIP-by-CUSIP) underlying every repo transaction conducted on the SIX Repo market against the SNB GC basket, we are able to assess whether the repo transactions under consideration are indeed CCY repo transactions, i.e. whether the cash leg is in a different currency from the collateral leg. These data are readily available to us in a time-consistent manner since the beginning of April 2011 for Swiss franc and since mid-October 2011 for US dollar transactions. For the period from October 2011 to July 31, 2017, we infer from the data that only 1.8% of the daily transaction volume with cash leg US dollar is secured by US

[16] A detailed description of the SNB's collateral framework can be found in Fuhrer, Müller, and Steiner (2017) and Swiss National Bank (2015).

dollar-denominated securities. The vast majority of the transaction volume is collateralized with securities denominated in Danish kroner (44%), Swiss francs (37%), and euros (14%). For transactions with cash leg Swiss franc and for the period from April 2011 to July 31, 2017, the vast majority is collateralized with securities denominated in Swiss francs (61%), Danish kroner (20%), and euros (14%). Although the dataset is restricted with respect to the sample period covered, we take this as strong evidence that US dollar repo transactions actually correspond to CCY repo trades. For transactions in Swiss francs, we are mostly dealing with conventional repo rates.[17]

5.2. *Institutional details of the GC Pooling Repo market*

The GCP market is one of the leading euro repo markets in terms of trading volume and participation (see European Central Bank (2012) and Mancini, Ranaldo, and Wrampelmeyer (2016) for a description of the GCP market). In contrast to the SIX Repo market, which is a triparty repo market, the GCP market is a central counterparty cleared market. While the euro market represents the major market segment, the GCP also allows for trading in US dollars, Swiss francs and pounds sterling. Trades in the GCP market are concluded on an electronic trading platform operated by Eurex Repo Ltd. In order to execute a trade in the GCP market, banks accept a quote on the platform and with the conclusion of the trade, Eurex Clearing becomes the legal counterparty of the banks involved in the trade. In this role, Eurex Clearing sends the settlement instruction to Clearstream, which triggers the reallocation of cash and collateral to the respective accounts on the settlement date.[18] Participants are almost exclusively banks domiciled in Europe, some with global reach while others are more focused on domestic markets. While the GCP Repo market has been operating since 2005 and thus information on euro repo trades have been available since then, US dollar repo trades have only been possible since the end of January 2010.

The GCP market is also regarded as a GC repo market and trades are concluded against

[17] As further discussed in Section 7.2 and 8, we argue that it is never optimal to acquire US dollar funding using US dollar-denominated collateral at the same interest rate if traders can resort to collateral denominated in a currency which exhibits a non-zero FX basis vis-à-vis the US dollar. The fact that all currencies mentioned above exhibit (substantial) FX bases when for instance calculated on the basis of OIS rates vis-à-vis the US dollar could be an explanation of the collateral selection pattern described above. Besides this, other cheapest-to-deliver arguments that might affect the collateral choice, internal risk-management requirements or regulatory considerations might also play a role. Finally, the collateral holdings and thus the likelihood for delivery in repo transactions might display a home bias.

[18] Note that cash and collateral exposures are only reallocated after a process called multilateral netting. That is, Eurex Clearing adds up all borrowing and lending exposures of each bank for each currency, secured by the same collateral basket and for the same settlement date, and reallocates only net cash and collateral exposures in the delivery-versus-payment process (overnight trades are settled non-netted and in real-time). Note that netting also takes place at the repurchase date of the repo transaction (including overnight transactions). The same conditions with regard to the currency and collateral apply.

the following four collateral baskets: the GCP ECB Basket, the GCP ECB Extended Basket, the GCP INT MXQ Basket, and the GCP Equity Basket. The GCP ECB Basket and the GCP ECB Extended Basket are subsets of the collateral which is eligible in the ECB's monetary policy operations and the GCP ECB Basket is regarded as the standard collateral basket, irrespective of the currency. Since January 2010, and in the euro (US dollar) segment, 64% (98%) of the outstanding volume was collateralized by the GCP ECB Basket.

The GCP ECB Basket consists of securities denominated in euros, issued by central banks, central, regional or local governments, supranational institutions and covered bonds. The potential volume of securities eligible for the GCP ECB Basket stood at 5,868 billion euros as of September 4, 2017. Since 2015, collateral in the GCP ECB Basket is exclusively denominated in euros. Before 2015, a selection of non-euro denominated securities including few US dollar-denominated securities were eligible, too. After 2015, we know that we are dealing with CCY repos in the case of repo transactions with cash-leg in US dollars and against the GCP ECB Basket. Before, we have to rely on anecdotal evidence suggesting that US dollar-denominated collateral was very rarely used.

For the GCP ECB Basket, ECB haircuts are used and, depending on the risk assessment by Eurex Clearing, an additional margin can be applied. Only securities in the GCP ECB Basket can be re-used in ECB open market operations as well as within the GCP market and for Eurex Clearing margin obligations, while all other collateral baskets only qualify for re-use in the latter two.

6. Data

The dataset used in this analysis consists of FX spot and forward rates as well as money market interest rates covering the period from January 1, 2006 to July 31, 2017 with business daily frequency including up to 2,689 observations. The maturities considered in the analysis include overnight (ON), one week (1W), and one month (1M).

The main analysis will be conducted for the USDCHF currency pair, which is chosen for two reasons: first, the USDCHF FX basis derived from LIBOR or OIS rates has been pronounced since the GFC. Deviations were economically significant over the past years and this has been true also in an environment with benign market risk, for instance, measured by the Chicago Board Options Exchange Volatility Index (VIX). In fact, among the G10 currency universe, the FX basis in the Swiss franc and the Japanese yen versus the US dollar have probably been most pronounced. Second, we have access to an extensive dataset of CCY repo transactions and collateral information underlying these transactions in Swiss francs and US dollars traded on the SIX Repo platform.

As a robustness check, the analysis is re-run for the EURUSD currency pair making use of transactions traded on the GCP Repo market operated by Eurex Repo Ltd. The EURUSD FX basis shares many commonalities with the USDCHF FX basis but it has been somewhat smaller, lately. Although the EURUSD currency pair is economically more relevant than the USDCHF currency pair, the focus is on USDCHF as we have a more comprehensive dataset for the latter.[19] In what follows, we describe the data used in the empirical analysis.

Spot and forward exchange rates: We use end-of-day rates (close price) of the New York trading session (5 p.m. New York time) for USDCHF and EURUSD FX spot rates and FX swap points. Data are downloaded from Bloomberg. Our analyses are based on mid-prices. The incorporation of transaction costs would result in a slight reduction of the CIP deviations documented below.

LIBOR rates: For the US dollar and Swiss franc, LIBOR rates fixed at 11 a.m. London time are downloaded from Bloomberg with business daily frequency.[20] For the euro, the corresponding reference rate EURIBOR is used. For ease of reference, we will subsequently not differentiate between the terms LIBOR and EURIBOR and just use the term LIBOR.

OIS rates: Close prices of US dollar and Swiss franc OIS rates are downloaded from Bloomberg with daily frequency. The floating leg of the US dollar interest rate is the Federal Funds Effective Rate. For the euro, the floating leg is the Euro Overnight Index Average (EONIA). In the case of the Swiss franc, TOIS fixing is used. All floating legs are unsecured money market rates with day-to-day maturity.[21]

Cross-currency repo rates: CCY repo rates are calculated based on transactions conducted on the multi-currency triparty repo platform operated by SIX Repo and the central counterparty cleared GCP Repo market. For the USDCHF (EURUSD) CIP deviation analysis, we calculate daily volume-weighted interest rates based on transactions concluded in the Swiss franc (Euro) and the US dollar segment on a given day. Only transactions concluded against the standard collateral basket used in the respective market are taken into account. For the sample period under consideration, the overall daily average turnover in the Swiss franc segment of the SIX Repo market was 5.3 billion Swiss francs and 1.8 billion US dollars

[19] See Bank for International Settlements (2016) for a comparison of the economic relevance of the two currency pairs.

[20] In what follows, will refrain from using the term 'business daily' but simply refer to daily observations.

[21] The OIS interest rate curve in Swiss franc is essentially a TOIS interest rate curve as the floating leg is a tomorrow-next and not an ON interest rate.

in the US dollar segment. In the 1W (ON, 1M) Swiss franc segment, the daily average turnover amounted to 0.3 (2.9, 0.2) billion Swiss francs. In the 1W (ON, 1M) US dollar segment, the daily average turnover amounted to 0.1 (1.4, 0.1) billion US dollars. For the GCP Repo market, US dollar transactions for the maturity contracts under considerations are only available starting from June 4, 2013. Thus, analyses relying on GCP Repo data range from June 2013 to July 31, 2017. For this sample period, the overall daily average turnover in the euro segment was 19.7 billion euros and 0.9 billion US dollars in the US dollar segment. In the 1W (ON, 1M) euro segment, the daily average turnover amounted to 0.6 (8.3, 0.1) billion euros. In the 1W (ON, 1M) US dollar segment, the daily average turnover amounted to 0.1 (0.2, 0.01) billion US dollars.

An overview of the data used and their sources is provided in Table 2. While acknowledging the above-documented inconsistencies in the timing as well as the ignorance of bid-ask spreads for the various instruments, we consider them to be of minor relevance for the analysis because their impact for our calculation is negligible relative to the CIP deviations found below.

Table 2: Data used and sources

Instrument	Currencies	Source	Remarks
Spot/forward ex. rates	USDCHF	Bloomberg	Mid-prices, NY close prices
LIBOR rates	USD, CHF	Bloomberg	11 a.m. London time
OIS rates	USD, CHF	Bloomberg	Mid-prices, close prices
CCY SIX Repo rates	USD, CHF	SIX Repo Ltd	Vol. w. average, SNB GC
CCY GCP Repo rates	USD, EUR	Eurex Repo Ltd	Vol. w. average, ECB GC

Table 2 provides an overview of the data used. The data described in row one to three are downloaded from Bloomberg. CCY SIX Repo rates are provided by SIX Repo and CCY GCP Repo rates are obtained from Eurex Repo Ltd. Both are not publicly available.

7. Empirical analysis

In this section, CIP deviations between the US dollar and the Swiss franc are analyzed over time and across different types of interest rates. Moreover, we examine the spread between US dollar CCY repo and US dollar OIS interest rates and show that this spread is a very good proxy for CIP deviations (the FX basis), in particular after 2014. This sheds light on the origins of the recent widening of the FX basis since 2014, which is still considered to be puzzling. Finally, we benchmark the findings of the USDCHF analysis with the analysis of EURUSD CIP deviations relying on CCY GCP Repo rates.

Our analysis is based on 1W instruments due to the following trade-off between market activity on the one hand and risk characteristics on the other. Trading in the SIX and GCP Repo markets is busiest in the ON and in the tomorrow-next (TN) segment while it is still decent for 1W contracts before decreasing quickly for longer-terms. The Bank for International Settlements Triennial Survey 2016 moreover suggests that roughly 70% of the FX swap turnover is in the maturity segment up to seven days (see Bank for International Settlements (2016)). From a data availability perspective alone, we should thus opt for the very short-end of the curve. However, as argued, deviations from CIP are driven by risk premia which are expected to increase with the duration of a contract. Due to their ultra-short maturity, ON and TN instruments can be considered as almost risk-less which makes these contracts inadequate for the purpose of our analysis. Anecdotal evidence from market participants moreover suggests that 1W to 3M maturities are common tenors for funding purposes whereas maturities below 1W are primarily traded due to daily liquidity management requirements, which are probably more mechanical in nature and not driven by arbitrage considerations.

7.1. CIP deviations across different interest rates

Subsequently, CIP deviations are calculated on the basis of the following sequence of transactions:

- **Step 1:** Take a 1W money market loan in US dollars
- **Step 2:** Enter a 1W sell and buy USDCHF FX swap transaction
- **Step 3:** Make a 1W loan in Swiss francs

If CIP held perfectly, the above trading program should yield a profit of zero. We run the calculation on daily data for the pre-crisis period which covers data from January 2006 to June 2007, the Global Financial Crisis (GFC) from July 2007 to December 2009, the sovereign debt crisis from January 2010 to December 2013, and the post-crisis period from January 2014 to July 31, 2017. Each period is analyzed separately for contracts running over quarter-ends and for contracts not running over quarter-ends. In this section, the analysis is conducted for CCY SIX Repo, LIBOR, and OIS interest rates, respectively.

Table 3 displays the number of observations by sub-period and by type of interest rate. Due to a lack of either Swiss franc or US dollar transactions in the 1W tenor on certain days, we have fewer CCY repo rate observations compared to LIBOR or OIS rate observations.[22]

[22]Note that money market rates in both currencies and for the same day are required to compute CIP deviations.

In order to avoid falling prey to a selection bias, the dataset for the empirical analysis is restricted to include only those days with observations across all types of interest rates shown in column five (dataset).[23]

Table 3: Number of observations for USDCHF analysis

Period	CCY SIX Repo	LIBOR	OIS	Dataset
Overall sample	1358	2689	2689	1358
Pre-crisis ex. Q-end	43	338	338	43
GFC ex. Q-end	243	536	536	243
Debt crisis ex. Q-end	579	844	844	579
Post-crisis ex. Q-end	376	731	731	376
Pre-crisis x Q-end	3	35	35	3
GFC x Q-end	18	50	50	18
Debt crisis x Q-end	62	86	86	62
Post-crisis x Q-end	34	69	69	34

Table 3 displays the number of observations used to calculate arbitrage profits based on 1W CCY SIX Repo, LIBOR, and OIS rates. The pre-crisis period covers data from January 2006 to June 2007, the GFC from July 2007 to December 2009, the sovereign debt crisis from January 2010 to December 2013, and the post-crisis period from January 2014 to July 31, 2017. The interaction between the various periods and quarter-ends denotes the number of observations where the contract runs over a quarter-end. In order to avoid a sample selection bias affecting our regression analysis, only days where interest rate information for every interest rate type is available are considered (see column five, dataset).

The following regression is estimated separately for CIP deviations calculated on the basis of CCY SIX Repo, LIBOR and OIS rates, respectively:

$$\begin{aligned} y_t = \beta_1 \cdot \textit{Pre-crisis ex. Q-end}_t + \beta_2 \cdot \textit{GFC ex. Q-end}_t + \beta_3 \cdot \textit{Debt crisis ex. Q-end}_t \\ + \beta_4 \cdot \textit{Post-crisis ex. Q-end}_t + \beta_5 \cdot \textit{Pre-crisis Q-end}_t + \beta_6 \cdot \textit{GFC Q-end}_t \\ + \beta_7 \cdot \textit{Debt crisis Q-end}_t + \beta_8 \cdot \textit{Post-crisis Q-end}_t + \epsilon_t. \end{aligned} \quad (5)$$

The dependent variable, y_t, represents CIP deviations in basis points on an annualized basis. The explanatory variable, *Pre-crisis ex.* $\textit{Q-end}_t$, is a dummy that takes the value of one for observations during the pre-crisis period excluding data points for contracts running over quarter-ends, and zero otherwise. The *GFC ex.* $\textit{Q-end}_t$, the *Debt crisis ex.* $\textit{Q-end}_t$ and the *Post-crisis ex.* $\textit{Q-end}_t$ are dummies that take the value of one for non-quarter-

[23]If we ran our estimations on different datasets across interest rates and if we were missing CCY SIX Repo data on days with excessively large or excessively small CIP deviations, a selection bias would arise. Consequently, it would become impossible to draw meaningful conclusions from comparing regression estimates across the three samples.

end observations during the GFC period between July 1, 2007 and December 31, 2009, the sovereign debt crisis period between January 1, 2010 and December 31, 2013 and the post-crisis period between January 1, 2014 and July 31, 2017, respectively. For the different periods, we moreover include dummies that take the value of one if transactions run over quarter-ends.[24] Standard errors are computed using the Newey-West heteroscedasticity and autocorrelation consistent procedure described in Newey and West (1987). We have chosen a lag length of eight to account for autocorrelation due to the time overlap resulting from taking 1W interest rates on a daily basis.[25] The regression estimates β_1 to β_4 hence capture within-quarter CIP deviations while the coefficients β_5 to β_8 capture quarter-end CIP deviations during the respective sub-periods.

Table 4 displays the regression results for the calculations based on CCY SIX Repo (Regression 1), LIBOR (Regression 2) and OIS rates (Regression 3), respectively. During the pre-crisis period, dislocations are small and only partially significant. This holds within as well as across quarter-ends and for all types of interest rates (see β_1 and β_5).[26] The estimates for β_2, β_3 and β_4 are all positive and highly significant, irrespective of the interest rate analyzed. For quarter-ends, we find that CIP deviations are considerably larger compared to within-quarter CIP deviations.

Comparing our estimates across the three regressions shows that deviations are generally largest when calculated on the basis of OIS rates, irrespective of the period under consideration and irrespective of whether we are investigating within-quarter data or data points running over quarter-ends. CIP seems to hold best when calculated on the basis of CCY SIX Repos. In fact, a paired t-test generally rejects the null hypothesis that the respective coefficient estimates are equal in size for the CCY SIX Repo, the LIBOR and the OIS regression. According to the test results in Table 5, CIP deviations differ significantly from each other during the sovereign debt and the post-crisis period, irrespective of whether we are looking at within- or across-quarter data. The test results are a bit less unambiguous for the GFC and the pre-crisis period, especially when looking at CIP deviations calculated on the basis of CCY SIX Repo as opposed to LIBOR rates.

In summary, our regression analysis reveals relatively large CIP deviations when calculated on the basis of OIS rates. That holds in particular for the post-crisis period, within-quarters as well as over quarter-ends and is in line with the findings documented in the

[24]The analysis is conducted on the basis of 1W instruments. If traded at time t, these instruments settle at $t + 2$ and at $t + 9$ for the near and for the far leg, respectively. Therefore, the *Q-end* dummies take on a value of one in the period from nine days to one day before the turn of a quarter.

[25]The results are robust with respect to the lag length definition as proposed by Greene (2003) which is to set the number of lags to the rounded up integer to the fourth root of the number of observations.

[26]The coefficient β_5 should be interpreted with care due to a lack of data observed over quarter-ends in the pre-crisis period.

Table 4: Deviations from CIP – Regression results

Period	(1) CCY SIX Repo	(2) LIBOR	(3) OIS
Pre-crisis ex. Q-end (β_1)	-2.80***	1.40	3.10***
	(-2.75)	(1.64)	(3.22)
GFC ex. Q-end (β_2)	14.20***	14.70***	45.10***
	(3.43)	(3.74)	(5.33)
Debt crisis ex. Q-end (β_3)	10.50***	20.20***	26.00***
	(5.32)	(11.08)	(12.67)
Post-crisis ex. Q-end (β_4)	18.80***	21.60***	49.20***
	(7.25)	(6.92)	(12.03)
Pre-crisis Q-end (β_5)	1.40	3.00***	6.00***
	(1.30)	(7.93)	(6.81)
GFC Q-end (β_6)	62.20	50.10*	92.80**
	(1.54)	(1.87)	(1.99)
Debt crisis Q-end (β_7)	19.80***	33.00***	39.50***
	(3.67)	(4.76)	(5.27)
Post-crisis Q-end (β_8)	74.10***	94.40***	123.70***
	(4.36)	(4.08)	(4.91)
Observations	1358	1358	1358
Adjusted R^2	0.12	0.14	0.16

Table 4 shows the coefficient estimates and the respective t-statistics from Equation (5) for the different money market rates under consideration. The pre-crisis period covers data from January 2006 to June 2007, the GFC from July 2007 to December 2009, the sovereign debt crisis from January 2010 to December 2013, and the post-crisis period from January 2014 to July 31, 2017. The *Q-end*-dummies take on a value of one in the period from nine days to one day before the turn of a quarter. The coefficient estimates are shown in basis points. (***), (**) and (*) denote statistical significance (one-tailed) at the 1%, 5%, and 10% significance level. t-statistics are in parentheses below the coefficients.

literature. CIP holds best when calculated on the basis of CCY SIX Repo rates although LIBOR-based deviations are also quite tight. By and large these results support our predictions from the arbitrage and risk-premium discussion: CCY repo and LIBOR rates both incorporate relative funding liquidity risk which also affects the pricing of FX swaps. This is in contrast to OIS rates, which are devoid of funding liquidity risk and, due to the fact that OIS-rates on their own are not funding instruments, do not allow for arbitrage.[27]

[27]The analysis of CIP deviations for the 1M maturity documented in Appendix B are in line with the findings of the 1W maturity analysis. CIP deviations are smallest for CCY SIX Repo rates. Moreover, CIP

Table 5: P-values of a paired t-test for β-estimates across regressions

Period	(1) CCY Repo vs. LIBOR	(2) CCY Repo vs. OIS	(3) LIBOR vs. OIS
Pre-crisis ex. Q-end (β_1)	0.00***	0.00***	0.00***
GFC ex. Q-end (β_2)	67.14	0.00***	0.00***
Debt crisis ex. Q-end (β_3)	0.00***	0.00***	0.00***
Post-crisis ex. Q-end (β_4)	0.00***	0.00***	0.00***
Pre-crisis Q-end (β_5)	47.68	18.09	5.21*
GFC Q-end (β_6)	19.77	0.01***	0.43***
Debt crisis Q-end (β_7)	0.00***	0.00***	0.00***
Post-crisis Q-end (β_8)	0.44***	0.00***	0.00***

Table 5 shows p-values from a paired t-test with unknown variance. According to the null hypothesis, the β-estimates are equal in size for the regressions shown in the respective columns of the table. The pre-crisis period covers data from January 2006 to June 2007, the GFC from July 2007 to December 2009, the sovereign debt crisis from January 2010 to December 2013, and the post-crisis period from January 2014 to July 31, 2017. The *Q-end*-dummies take on a value of one in the period from nine days to one day before the turn of a quarter. (***), (**) and (*) denote statistical significance (one-tailed) at the 1%, 5%, and 10% significance level.

7.2. A proxy measure for the FX basis

It has been shown previously that CIP fails when calculated on the basis of OIS rates while it holds relatively well when calculated on the basis of CCY repo rates. An implication from this is that the CCY repo rate differentials incorporate a large fraction of the FX basis found in OIS-based CIP calculations. We claim that the US dollar and not the Swiss franc CCY repo rate is key for this finding. That is, the US dollar CCY repo rate incorporates a large fraction of the OIS-based FX basis. Two hypothesis can be derived from this conjecture: first, the US dollar CCY repo rate should trade above conventional US dollar money market rates that are devoid of the FX basis, such as OIS rates. Second, the spread between US dollar CCY repo and US dollar OIS rates should approximate OIS-based USDCHF CIP

deviations calculated based on LIBOR or OIS rates are found to be higher in the 1M tenor than for the 1W maturity, while the difference in CIP deviations based on CCY SIX Repo rates is not statistically significant. Thus, the evidence found supports our hypothesis that CIP deviations tend to increase with the maturity of the contract when calculated on the basis of LIBOR or OIS rates.

deviations.[28]

Figure 1 depicts US dollar CCY SIX Repo rates (black line), US dollar OIS rates (red line) and the USDCHF FX basis derived from OIS interest rate differentials, all shown for a maturity of one week. Recall that US dollar CCY SIX Repo rates are not available on a daily basis, which explains the missing observations compared to US dollar OIS rates in Figure 1. The following observations can be made: first, US dollar CCY SIX Repo rates indeed trade above US dollar OIS rates. Second, the USDCHF FX basis spikes towards quarter-ends. 1W US dollar OIS rates fail to capture these dynamics while 1W US dollar CCY SIX Repo rates interestingly exhibit similar quarter-end spikes.

Fig. 1. US dollar CCY SIX Repo, US dollar OIS interest rates and the USDCHF FX basis

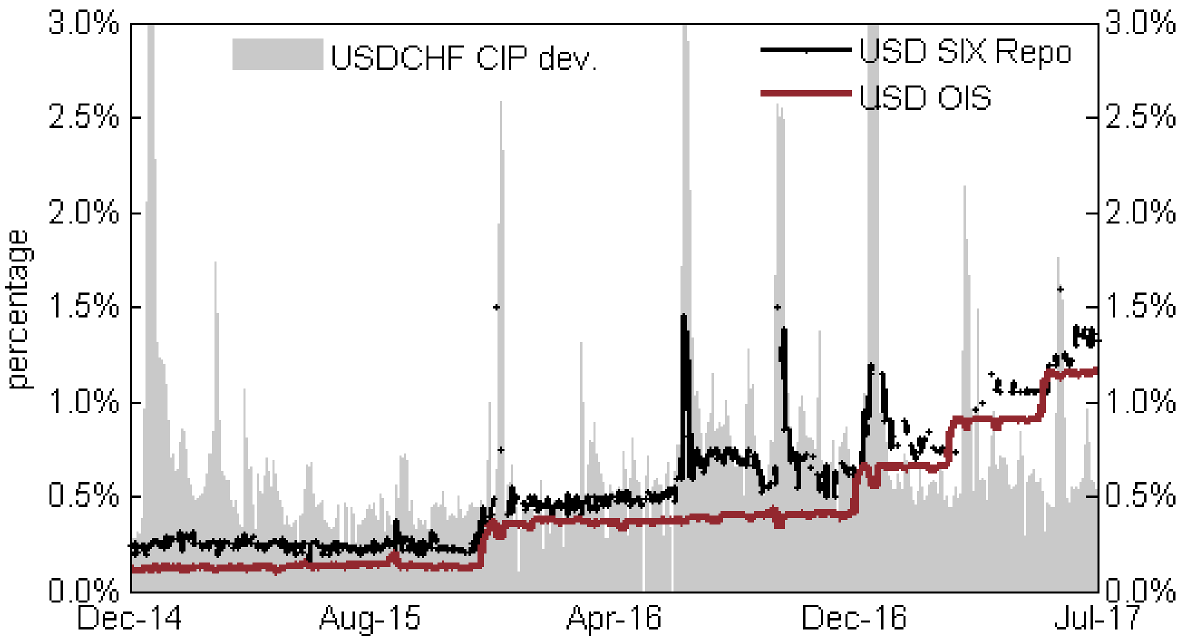

Figure 1 shows US dollar CCY SIX Repo rates (black line), US dollar OIS rates (red line) and the USDCHF OIS-based FX basis (grey shaded). All instruments are depicted for a maturity of one week.

These stylized facts are first evidence that the spread between US dollar CCY repo and US dollar OIS rates on the one hand and OIS-based CIP deviations on the other move very much in parallel, in particular, over quarter-ends. To provide further evidence for our hypothesis, the predictive power of the spread between US dollar CCY SIX Repo and US

[28]In fact, there is hardly any price difference between Swiss franc CCY repo and Swiss franc OIS rates or between euro CCY repo and euro OIS rates. The same is not true for US dollar interest rates where CCY repos trade at a considerable and persistent premium compared to OIS. It is hence the US dollar CCY repo which makes the difference when testing CIP in Equation (2).

dollar OIS interest rates for the FX basis is analyzed across time. For that purpose, the following regression model is estimated on a rolling window basis with a lag length of 400 observations:

$$y_t = c + \beta \cdot Proxy_t + \epsilon_t. \tag{6}$$

The independent variable, y_t, represents CIP deviations between the US dollar and the Swiss franc derived from OIS interest rate differentials. In addition to the constant, c, the regression has only one explanatory variable: our proxy measure for the FX basis which corresponds to the spread between US dollar CCY SIX Repo and US dollar OIS interest rates, specified as $Proxy_t$. The results are shown in Figure 2. The estimate for β shown in the left-hand side panel is positive throughout the entire sample and apart from a short-lived period towards the beginning of 2015, which falls together with the abandonment of the EURCHF floor by the SNB, the results are significant. The adjusted R^2 shown in the right-hand side panel is positive, oscillating at around 20% between mid-2011 and mid-2016. It rises sharply thereafter to reach more than 70%. We attribute this increase to the fact that our proxy captures quarter-end dynamics well, which constitute a more recent phenomenon.

Fig. 2. Deviations from CIP on proxy measure – Rolling regression for USDCHF

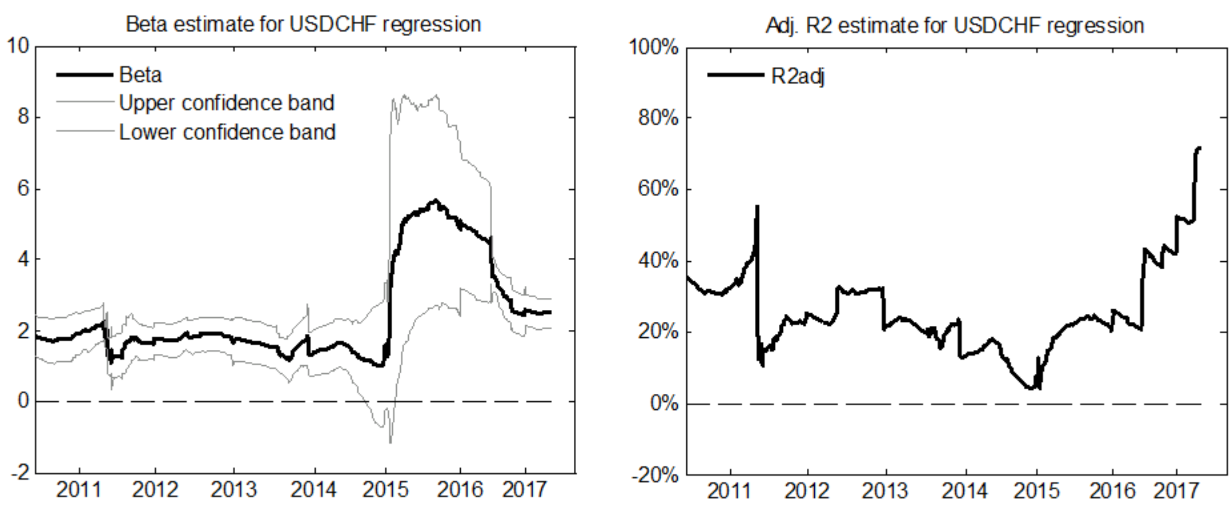

Figure 2 depicts the results from regressing OIS-based deviations from CIP in USDCHF on a constant and on a proxy measure for the FX basis calculated as the difference between US dollar CCY SIX repo and US dollar OIS interest rates. The regression is conducted on a rolling window basis with a window length of 400 days. The panel on the left shows the regression estimate β (solid black line) and its lower and upper confidence band (light grey lines). The confidence band has a width of -1.96 to +1.96 standard deviations and hence covers 97.5% of all outcomes. The panel on the right shows the adjusted R^2. The regression is based on daily data from January 1, 2006 to July 31, 2017.

We have shown empirically that the spread between US dollar CCY repo rates and US dollar OIS interest rates is indeed a fairly good proxy for the FX basis and this is particularly true after 2014. The crucial element for this finding is the US dollar CCY repo rate that incorporates a considerable part of the FX basis. We do not expect the proxy to fit perfectly because the underlying transactions are very similar but not identical: the US dollar CCY repo rate involves the exchange of cash and collateral, whereas the FX swap involves the exchange of cash in two currencies. In other words, if there is a premium involved in the exchange of (high-quality liquid) collateral into cash, the proxy is not perfect.

Another way to show that the spread between US dollar CCY repo rates and US dollar OIS interest rates approximates the FX basis is the following theoretical arbitrage argument: take an investor borrowing, say, US dollars in the CCY repo market collateralized by securities denominated in Swiss francs. He could arrive at the very same exposure by borrowing Swiss francs in a conventional repo transaction, i.e. against collateral denominated in Swiss francs, and by changing the proceeds in a buy and sell USDCHF FX swap transaction. These two strategies should bear the same cost because in both cases the investor has initiated the transactions with Swiss franc collateral and ends up with US dollars. In other words, the US dollar CCY repo rate must correspond to the Swiss franc interest rate of a conventional repo augmented by the price of the USDCHF FX swap. Or put differently, the USDCHF FX basis based on conventional repo rate differentials corresponds to the interest rate differential between US dollar CCY repo and US dollar conventional repo rates. To see this more clearly, Equation (2) is rewritten as follows:

$$f_{t,t+1} - s_t + i_{t,t+1}^{Repo,CHF} = i_{t,t+1}^{Repo,USD} + \epsilon_{t,t+1}, \tag{7}$$

where $f_{t,t+1}$, s_t, $i_{t,t+1}^{Repo,USD}$ and $i_{t,t+1}^{Repo,CHF}$ correspond to the USDCHF forward exchange rate, the USDCHF spot exchange rate, the US dollar conventional repo rate and the Swiss franc conventional repo rate. The variable $\epsilon_{t,t+1}$ represents the conventional repo based USDCHF FX basis. According to the argumentation above, the left-hand side of Equation (7) must be equal in size to the US dollar CCY repo rate which allows us to rewrite Equation (7) as follows:

$$i_{t,t+1}^{CCY\,Repo,USD} = i_{t,t+1}^{Repo,USD} + \epsilon_{t,t+1}, \tag{8}$$

where $i_{t,t+1}^{CCY\,Repo,USD}$ represents the US dollar CCY repo rate.

It follows from these theoretical arbitrage argument that we ideally had 1W US dollar conventional repo rates collateralized by high-quality, liquid fixed-income securities denominated in US dollar at our disposal to test the proxy measure's quality to approximate the FX basis. Unfortunately and to the best of our knowledge, such a benchmark repo rate does not exist and this is why our empirical analysis focuses on the spread to 1W US dollar OIS rates, instead. Note, however, that the OIS rate should be a reasonable proxy for the conventional repo rate as both instruments are devoid of counterparty credit risk and do not incorporate relative funding liquidity risk (see Section 3).

Note that the spread between US dollar CCY repo rates and US dollar conventional repo or OIS rates does not only approximate the FX basis, but it also reflects relative funding liquidity risk. This can be seen from Table 1 where CCY repos are shown to incorporate relative funding liquidity risk while conventional repo and OIS rates do not. In view of the empirical results, this indicates that the presence of a heightened relative funding liquidity risk premium can explain OIS-based CIP deviations after 2014 at least partially. In addition to that, our theoretical considerations highlight that the basis must affect cash and collateral markets equally by arbitrage. After all, the two US dollar repo rates used to approximate the FX basis only differ with respect to the collateral provided in the transaction. While the US dollar CCY repo transaction is based on Swiss franc collateral, the conventional US dollar repo is conducted against US dollar securities. Our findings moreover contribute towards clarifying why conventional repo rates should not be used when testing CIP as, for instance, proposed in Du et al. (2017). Conventional repo rate differentials fail to reflect relative funding liquidity risk. In addition, they do not allow to conduct CIP arbitrage in practice because an arbitrageur would need US dollar collateral in the first place to acquire US dollar cash via conventional repo markets. Trying to fund US dollar collateral would, however, contribute towards driving CIP deviations closer to zero already.

7.3. Robustness of results

To test our results for robustness, the preceding analysis is broadened in two respects: first, CIP deviations between the euro and the US dollar are examined. Second, the analysis is conducted on the basis of GCP Repo data. Unfortunately, the US dollar segment on the GCP Repo market was only launched in January 2010 and 1W US dollar contracts only trade on a regular basis since July 31, 2013. Thus, the analysis covers a shorter period than the analysis of CCY SIX Repo data. Again, the focus is on 1W contracts and we benchmark the results against CIP deviations obtained when using LIBOR and OIS rates.

Table 6 displays the number of daily observations by interest rate type and sub-period for the EURUSD CIP regression. Due to limited data availability, the analysis is restricted to the

Table 6: Number of observations for EURUSD analysis

Period	CCY GCP Repo	LIBOR	OIS	Dataset
Overall sample	502	940	940	502
Debt crisis ex. Q-end	75	86	86	75
Post-crisis ex. Q-end	395	770	770	395
Q-end	32	84	84	32

Table 6 displays the number of observations used to calculate deviations from CIP based on 1W CCY GCP Repo, LIBOR, and OIS rates, respectively. The analysis runs from July 31, 2013 to July 31, 2017. The quarter-end dummy denotes the number of observations where the contract runs over a quarter-end. In order to avoid a sample selection bias affecting our regression analysis, only days where interest rate information for every interest rate type is available are considered (see column five, dataset).

sovereign debt crisis (row two) and the post crisis period (row three). Row four displays the number of observations where the 1W contract runs over quarter-ends. Quarter-end effects are shown for the entire sample and not for each sub-period as in the USDCHF analysis. The dataset for the regression is again restricted to days with interest rate information on all types of interest rates (see column five, dataset). The following OLS regression is estimated:

$$y_t = \beta_1 \cdot \textit{Debt crisis ex. Q-end}_t + \beta_2 \cdot \textit{Post-crisis ex. Q-end}_t + \beta_3 \cdot \textit{Q-end}_t + \epsilon_t. \tag{9}$$

The variable to be explained, y_t, represents CIP deviations between the euro and the US dollar based on CCY GCP Repo, LIBOR and OIS rates, respectively. The coefficients β_1 and β_2 capture within-quarter CIP deviations during the sovereign debt crisis period from July 31, 2013 to December, 2013 and the post-crisis period from January 2014 to July 31, 2017. The quarter-end dummy takes on a value of one in the period from nine days to one day before the turn of a quarter and hence captures CIP deviations over quarter-ends.

Table 7 displays the regression results for the three regressions based on CCY GCP Repo (column one), LIBOR (column two) and OIS rates (column three). CIP deviations are positive across all time periods and for all regressions and the coefficients are significant.[29] Note that CIP holds relatively well when calculated on the basis of CCY GCP Repo rates. After all, average deviations are much smaller in size in Regression (1) compared to Regressions (2) and (3) for all samples analyzed. In particular, that is true for CIP deviations calculated based on contracts running over quarter-ends. The results of the paired t-test

[29] The moderate size of the deviations during the sovereign debt crisis period should be interpreted with care. After all, the number of observations falling into the sovereign debt crisis period is relatively small (see Table 6) because data is only available as of July 31, 2013. The regression analysis based on SIX Repo rates in Section 7.1 draws on a much longer dataset.

Table 7: Deviations from CIP – regression results for EURUSD

Period	(1) CCY GCP Repo	(2) LIBOR	(3) OIS
Debt crisis ex. Q-end (β_1)	1.70***	5.70***	9.80***
	(5.52)	(9.75)	(16.40)
Post-crisis ex. Q-end (β_2)	3.50***	16.10***	19.60***
	(7.06)	(9.34)	(10.17)
Q-end (β_3)	17.40*	45.60**	50.50**
	(1.76)	(2.12)	(2.21)
Observations	502	502	502
Adjusted R^2	0.08	0.10	0.09

Table 7 shows the coefficient estimates and the respective t-statistics from Equation (9) for the different money market rates under consideration. The regression runs from July 31, 2013 to July 31, 2017. Due to lack of historical data, the sovereign debt crisis covers data from July 31, 2013 (instead of January 2010 as in the previous analysis) to December 2013, and the post-crisis period from January 2014 to July 31, 2017. The *Q-end*-dummy takes on a value of one in the period from nine days to one day before the turn of a quarter. The coefficient estimates are shown in basis points. (***), (**) and (*) denote statistical significance (one-tailed) at the 1%, 5%, and 10% significance level. The t-statistics are in parentheses below the coefficients.

Table 8: P-values of a paired t-test for β-estimates across regressions

Period	(1) CCY Repo vs. LIBOR	(2) CCY Repo vs. OIS	(3) LIBOR vs. OIS
Debt crisis ex. Q-end (β_1)	0.00***	0.00***	0.00***
Post-crisis ex. Q-end (β_2)	0.00***	0.00***	0.00***
Q-end (β_3)	0.00***	0.00***	0.00***

Table 8 shows p-values from a paired t-test with unknown variance. According to the null hypothesis, the β-estimates are equal in size for the regressions shown in the respective columns of the table. The regression runs from July 31, 2013 to July 31, 2017. Due to lack of historical data, the sovereign debt crisis covers data from July 31, 2013 (instead of January 2010 as in the previous analysis) to December 2013, and the post-crisis period from January 2014 to July 31, 2017. The *Q-end*-dummy takes on a value of one in the period from nine days to one day before the turn of a quarter.

shown in Table 8 confirm that differences across the regression coefficients are indeed highly significant.

To summarize, CIP between the euro and the US dollar holds much better when calculated on the basis of CCY GCP Repo rates and in particular over quarter-ends. This suggests that US dollar CCY GCP Repo rates capture the FX swap pricing and this is particularly true on quarter-end. The results of the CIP analysis using US dollar CCY GCP Repo rates thus confirm the findings of the US dollar CCY SIX Repo rate analysis. Figure 3 shows US dollar CCY GCP Repo (black line), US dollar OIS rates (red line) and the EURUSD OIS-based FX basis (grey area). All instruments are again shown for a maturity of one week. Recall that US dollar CCY GCP Repo rates are not available on a daily basis. The dynamics of the US dollar CCY GCP Repo rate are indeed very similar to those of the US dollar CCY SIX Repo market. The US dollar CCY GCP Repo rate trades as well above OIS and it exhibits similar quarter-end spikes.

Fig. 3. US dollar CCY GC Repo, US dollar OIS interest rates and EURUSD FX basis

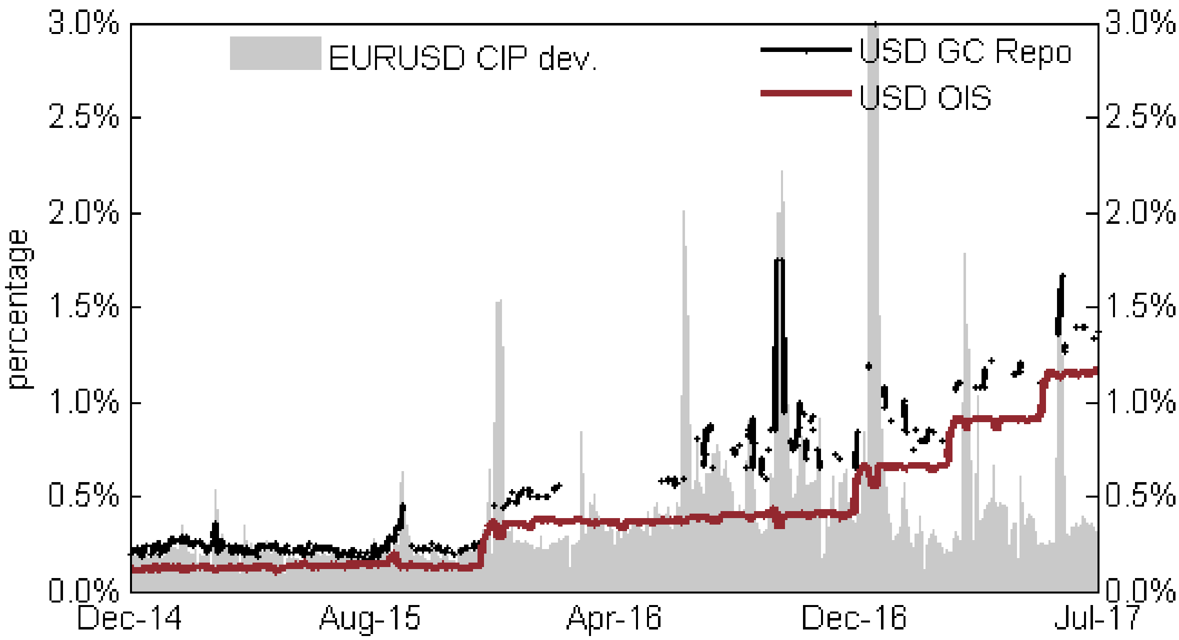

Figure 3 shows US dollar CCY GCP Repo rates (black line), US dollar OIS rates (red line) and the EURUSD OIS-based FX basis (grey area). All instruments are depicted for a maturity of one week.

8. Discussion of results

The theoretical considerations and empirical analyses have shown that irrespective of the interest rate analyzed, CIP deviations were generally small and insignificant during the pre-crisis period. CIP deviations only emerged thereafter. The size of these deviations, however, differs depending on the type of interest rate used when calculating CIP. Deviations are found to be large and statistically significant when calculated on the basis of OIS as opposed to CCY repo rates. CIP deviations based on CCY repo rates tend to be also smaller than those based on LIBOR rates. Finally, CIP violations derived from OIS and LIBOR rates generally increase across quarter-ends, in particular, during the post-crisis period, while quarter-end effects are significantly smaller when CIP is calculated on the basis of CCY repo rates.[30]

These findings are in line with our arbitrage and risk premium considerations, where we argue that CCY repos allow for CIP arbitrage and that CCY repo rate differentials are subject to the same risk dynamics as the corresponding FX swap instrument. Both are almost devoid of counterparty credit risk but incorporate a relative funding liquidity risk premium. CIP should therefore hold more tightly when calculated on the basis of CCY repo compared to OIS and to a lesser extent compared to LIBOR rates. We interpret this as evidence that relative funding liquidity risk is most important in explaining CIP deviations, which is in accordance with the findings by Rime et al. (2017). Note that the findings are also consistent with the observation that CIP is practically inexistent before the GFC for all interest rates under consideration and irrespective of the currency pair analyzed under the assumption that relative funding liquidity risk and counterparty credit risk hardly mattered in the pre-crisis period.

The analysis has also shown that US dollar CCY repo rates trade at a mark-up relative to comparable US dollar money market rates and that US dollar CCY repo rates exhibit quarter-end spikes, which is not the case for other US dollar interest rates. This is due to the fact that the FX basis affects US dollar CCY repo rates because the underlying collateral of the CCY repo transaction is usually denominated in a non-US dollar currency. As a consequence, the difference between US dollar CCY repo and US dollar OIS rates amounts to a powerful proxy for the OIS-based USDCHF FX basis, in particular after 2014. Note that this supports our hypothesis that relative funding liquidity risk is the driving force behind OIS-based CIP deviations because US dollar CCY repo incorporates relative funding liquidity risk, while it does not affect US dollar OIS rates.

A set of wide ranging (policy) implications can be derived from our findings: first, it has been shown that CCY repo rates incorporate the FX basis. This implies that the basis does not only enter transactions where cash is exchanged against cash like in FX swaps, but also transactions were cash is exchanged against collateral in another currency such as in CCY repos or transactions where collateral in one currency is exchanged against collateral in another currency. We understand this to be the result of the high-quality liquid collateral

[30]Another interesting result to mention here is that CIP deviations calculated on the basis of LIBOR or OIS tend to rise with increasing maturity of the underlying instrument. No such maturity effect seems to exist for deviations derived from CCY repo rates (see Appendix B).

underlying the transactions analyzed, which allows to convert collateral into cash any time at a small premium. Thus, the impact of the basis should be quantitatively and qualitatively the same in all three transaction types.

Second, it follows from the above that market participants should not only exhibit a preference for US dollar cash but also for US dollar collateral compared to cash or collateral in other currencies because under perfect convertibility and/or if the funding cost of the underlying financial transaction is reflected in its price, the collateral market inherits the funding liquidity characteristics of the corresponding cash market. In other words, we expect the relative funding liquidity premium found in the FX swap pricing to be incorporated also in the price to exchange, say, US dollar and Swiss franc collateral of the same quality. Note that there exists a market for temporary collateral exchanges and the transaction to do so is called "securities lending and borrowing" (SLB). Unfortunately, we are not aware whether it is market practice for SLB-transactions to also exchange collateral in different currency denomination.[31]

Third, the collateral delivered in a CCY repo transaction should be a function of the basis. The borrower in such a transaction will most likely not deliver US dollar collateral because it is more valuable than collateral in other currencies. In fact, as documented in Section 5.1, US dollar CCY repos conducted in the SIX CCY Repo market are collateralized with securities denominated in Danish kroner (44%), Swiss francs (37%), and euros (14%). The FX basis between the US dollar on one side and the Swiss franc, the Danish kroner and the euro on the other is quantitatively indeed large and similar across all three currency pairs which might render collateral in these currencies cheapest-to-deliver.[32]

Fourth, our results provide an interesting perspective on the central bank swap lines which were installed among the major central banks during the GFC to alleviate US dollar funding tensions. The central bank swap line allows non-US banks to get hold of US dollar liquidity through their home central bank via repo transactions against collateral eligible at the respective central bank. Due to the fact that central banks primarily accept collateral denominated in their domestic currency, US dollar funding via the swap line is accessed via a CCY repo. According to the findings of our paper, it is exactly because of the CCY repo nature that the central bank swap line represents a very powerful tool to calm US dollar funding tensions. The mechanism at work is that the swap line limits the relative funding

[31] Anecdotal evidence provided in Pozsar (2017) suggests that Japanese banks swap Japanese government bonds for US Treasuries with the Japanese Ministry of Finance at negligible cost. Subsequently, Japanese banks acquire US dollar in the repo market against the US Treasuries. This is named as one reason for the relatively stable FX basis between US dollar and Japanese yen in 2017, which suggests that there is indeed the link between the collateral and the cash market described above.

[32] Other arguments such as a possible home bias in the banks' collateral pool, internal risk-management considerations or regulatory requirements might also play a role for the collateral selection.

liquidity premium of the swap line central bank currencies vis-à-vis the US dollar.[33] In contrast, the central bank swap line is ineffective in reducing the counterparty credit risk premium as long as participating central bank do not relax their collateral policy.

Fifth, in contrast to a large literature explaining CIP deviations, regulation is not at the center of our explanation. Despite this, we conjecture that our explanation, which emphasize the choice of the right interest rate for CIP-testing purposes and the regulatory perspective are not mutually exclusive. If the relative funding liquidity premium incorporated in CCY repo rates is affected by regulation, the two explanations are in fact complementary. As motivated above, the relative funding liquidity premium ultimately expresses the preference for holding one currency, collateral denominated in one currency or even liquid assets denominated in one currency over the other. Different regulatory treatment across currencies could very well explain this observation. Moreover, it might also explain why quarter-end spikes are observed in case of US dollar CCY repo rates after 2014, while no such quarter-end dynamics are observed in US dollar OIS rates (see Figure 1 and 3).[34] Different regulatory treatment across jurisdictions is also brought forward as an explanation for CIP quarter-end dynamics in Du et al. (2017).

Sixth, note that our paper reveals an inconsistency in the regulatory treatment (and accounting standard) of CCY repos and FX swaps. Although from an economic perspective, the two transactions are very similar if not identical, the Leverage Ratio and the Liquidity Coverage Ratio treatment of the two transactions differ.

Finally, neither the related studies discussed nor our paper can pinpoint the exact sources of the relative funding liquidity premium. In particular, it is not understood why almost all currencies exhibit such a pronounced relative funding liquidity premium vis-à-vis the US dollar. We can only speculate that the role of the US dollar as the dominant currency in the global funding and settlement markets, linked with highly developed and liquid US financial markets as well as central bank policies, could be important drivers.

9. Conclusion

Arbitrageurs might run into practical difficulties when trying to exploit deviations from CIP. The crux is choosing the right money market rate when setting up the arbitrage trade. Interest rate differentials based on CCY repo rates take account of relative funding liquidity

[33] According to the current definition, the rate in the central bank swap line is determined at the US dollar OIS rate plus 50 basis points. Given the fact that OIS exhibits no funding liquidity risk, the relative funding liquidity premium of the swap line central bank currencies should theoretically be limited at the size of around 50 basis points.

[34] Note that most of the Basel III regulatory reforms became effective as of 2015.

risk between currency areas and feature close to zero counterparty credit risk. As a matter of fact, the risk characteristics of CCY repo interest rate differentials are essentially the same to those of an FX swap transaction. Due to this identical risk structure, CCY repos allow for true CIP arbitrage. While CIP should therefore hold using CCY repo rates, this is not necessarily the case for OIS or LIBOR interest rates. Although LIBOR rate differentials should correctly reflect relative funding liquidity risk, they are unsuitable when putting CIP to the test because they feature (relative) counterparty credit risk. OIS rates incorporate hardly any funding liquidity or counterparty credit risk and they do not allow for CIP arbitrage. Thus seem to be unsuitable, too.

This paper shows empirically that the parity relationship holds more tightly when running CIP calculations on the basis of CCY repo as opposed to OIS or LIBOR rates. The analysis of CCY rates relies on repo market data from the SIX and GCP multi-currency repo platform. Our analysis suggests that the widely reported departure from CIP vis-à-vis the US dollar, in particular since 2014, can mainly be attributed to the presence of a positive and persistent relative funding liquidity premium. The relative funding liquidity premium arises due to a preference for liquidity in certain currencies, for instance US dollar, as opposed to others. Over quarter-ends, we find that US dollar CCY repo interest rates tend to spike, in tandem with the FX basis vis-à-vis the US dollar. In other words, investors are willing to pay a premium to get hold of US dollars, and this is even more pronounced over quarter-ends. Potential reasons could be regulation or window-dressing.

Besides being an attempt to solve the CIP puzzle of which the main takeaway is that there is no CIP puzzle when considering the right interest rates, our paper has several policy implications. In our view, the most interesting insight is that central bank swap lines are a strong tool to relieve US dollar funding stress exactly because they are designed as CCY repos. That is, non-US banks are able to access US dollar funding at their home central bank against non-US dollar collateral.

Appendix A. Description of money market rates

A.1. Overnight-index swap rates

An OIS agreement is an interest rate swap where one party agrees to pay a fixed interest rate on a certain principal amount in exchange for a floating interest rate on the same principal amount during the term of the contract. The floating leg of the agreement is usually tied to an ON rate. There are no cash flows until the contract matures when the net difference between the realized ON interest rate, averaged over the term of the contract, and the pre-defined fixed interest rate, is settled.

The net profit or replacement cost is usually subject to frequent margin calls, which is why the OIS agreement on its own involves no counterparty credit risk. Nevertheless, OIS interest rates are not entirely devoid of counterparty credit risk due to the floating leg which is an unsecured interbank transaction and thus incorporates counterparty credit risk. A similar argument applies when it comes to the funding liquidity premium. Except for potential margin calls and the net settlement payment at the end, an OIS agreement ties up no liquidity. In particular, unlike an FX swap, it does not involve an exchange of notional amounts at the beginning of the contract. OIS interest rates are nevertheless potentially affected by a small funding liquidity premium through the floating leg.

It is often overlooked that the exploitation of CIP deviations based on OIS rates involves a so-called rollover risk. A CIP arbitrageur can only log in the fixed leg interest rate if capable of borrowing and lending at the ON interest rate underlying the OIS agreement for the entire length of the contract. If an investor is unable to tap the ON market at these rates, for instance, due to a deterioration in his credit quality during the term of the contract, he will fail to reap (all) arbitrage profits. Note that the longer the contract, the higher this risk is. In other words, the rollover risk should increase with the maturity of the OIS contract implying that the mismatch in risk exposure between the left- and the right-hand side of Equation (2) should rise with longer maturities and thus CIP deviations should, in principle, increase.[35]

A.2. LIBOR

Numerous studies analyze the CIP relationship on the basis of LIBOR. The LIBOR reflects the interest at which prime banks are able to borrow on an unsecured basis for

[35] Rime et al. (2017) outline the sequence of transactions when striving to secure a CIP arbitrage profit on the basis of OIS rates. They also discuss associated rollover risks.

different maturities.[36] It is therefore not an ideal interest rate for CIP testing purposes, because the LIBOR incorporates a counterparty credit risk premium component while an FX swap is exempt from such risks. This difference could result in a residuum when putting Equation (2) to test. Proponents of the LIBOR might argue that the counterparty credit risk premium is likely to affect domestic as well as foreign interest rates and thus cancels out on the right-hand side of Equation (2). However, the composition of the LIBOR panel differs from currency to currency so that the counterparty credit risk component in the two currencies underlying the FX swap is usually not equal in size.[37]

The LIBOR does a better job when it comes to capturing the funding liquidity risk component. Lending in the LIBOR market results in liquidity being tied up until the contract matures. Therefore, differences in the funding liquidity premium across currencies are fully reflected in LIBOR interest rate differentials.

Although widely used as a reference rate in financial contracts, the representative content of the LIBOR to reflect overall interbank funding conditions is questionable. This is because LIBOR is based on quotes of the submitting prime banks and because of a general decline in the underlying market of unsecured interbank transactions during and after the GFC. Reports of manipulative behavior add to reservations.[38] In other words, it cannot be taken for granted that a CIP arbitrage can effectively be set up based on LIBOR interest rates.

A.3. Conventional repo rates

While the collateral provider remains entitled to coupon and interest payments on the securities provided, legal ownership is usually transferred to the cash lender, which puts him in a position to liquidate the securities received if confronted with a sudden liquidity need. The optionality to sell or to re-use the collateral, for instance in another repo transaction, combined with the fact that the collateral is denominated in the same currency as the cash loan results in a relatively low funding liquidity premium.[39] Note that the resulting funding

[36] Strictly speaking, LIBOR represents an indicative ask interest rate, i.e. the rate at which a prime bank could borrow unsecured. When calculating CIP deviations based on LIBOR, the rate is also used for the rate at which the currency received in the FX swap can be invested, i.e. the bid interest rate. In the paper, we follow the practice in the literature and use LIBOR as a proxy for general unsecured funding conditions.

[37] There is a cross-sectional difference between LIBOR-OIS spreads for different currencies, which is evidence that the relative counterparty credit risk premium is non-zero.

[38] During the GFC some contributors resorted to understating their borrowing costs in order to avoid the perception that their default risk had deteriorated. Others manipulated contributions with the goal of making a profit on derivative positions referencing to the LIBOR (see, for instance, Duffie and Stein (2015)).

[39] Exercising the re-use option exposes the investor to market risk. After all, at the expiration date of the contract, he needs to return securities of similar quality to his repo counterpart. However, a short-position in highly rated (government) bonds is much less risky than an open currency position due to the former's lower price volatility. The collateral receiver could moreover avoid risks related to unfavorable price movements by re-using the collateral received in an offsetting reverse repo transaction. Unlike FX swap points, which

liquidity premium is somewhat different from the relative funding liquidity premium inherent in an FX swap transaction because the latter involves an exchange of assets (cash) in two currencies while the former represents an exchange of assets (cash and collateral) in one currency. We are of the opinion that the funding liquidity premium should be relatively small if cash and collateral are denominated in the same currency. Collateral of high quality should be convertible into cash with relative ease, even in times of stress, not least due to the central bank discount window or emergency liquidity facilities where such collateral could be pledged against liquidity should the need arise.

Appendix B. USDCHF CIP deviations across maturities

It has been shown above that FX swaps and CCY repo interest rate differentials move largely in parallel. LIBOR and OIS interest rate differentials, by contrast, fail to capture FX swap price dynamics. We attribute this finding to risk factors affecting FX swaps and CCY repo interest rate differentials similarly. Both these instruments are subject to relative funding liquidity risk while being devoid of counterparty credit risk, we argue. LIBOR and OIS interest rate differentials, by contrast, obey different risk dynamics. Risk premium aspects become increasingly relevant for longer-term contracts. The gap in risk coverage between an FX swap position on the hand and a LIBOR or OIS interest rate differential position on the other should thus increase for longer-term instruments. We hence expect CIP deviations to rise in maturity when calculated on the basis of LIBOR or OIS but not when calculated on the basis of CCY repo interest rate differentials.

Table 9 supports this hypothesis. It displays the results of six regressions with CIP deviations between the US dollar and the Swiss franc as dependent variable and a constant reflecting average CIP deviations as explanatory variable. The deviations are either derived from CCY SIX Repo rates (row one), LIBOR rates (row two) or OIS rates (row three). The results for the constant differ depending on the maturity analyzed. The regressions are run on the basis of 1W (column one) and 1M (column two) instruments. The analysis indeed reveals that CIP deviations calculated on the basis of OIS and LIBOR increase in the maturity. A paired t-test confirms this finding by showing that the increase is significantly

exhibit large price swings in response to changing liquidity scarcity levels, repo rates should respond in a more lethargic manner to a liquidity squeeze. Moreover, as long as there is a lender of last resort offering cash against collateral, market participants with central bank access should always be willing to provide liquidity against such collateral. Consequently, even in times of stress, it should not become prohibitively expensive to enter an offsetting reverse repo position to cover sudden liquidity needs. See Fuhrer et al. (2016) for an empirical analysis of the re-use of collateral.

when moving from the one week to the one month maturity in the case of LIBOR- and OIS-based calculations (see Table 10). This is in contrast to CIP deviations based on CCY SIX Repo rates, where average CIP deviations between the two maturities are almost the same. For the CCY regression, the null hypothesis according to which the two coefficients are equal in size cannot be rejected.

Table 9: Deviations from CIP across maturities and instruments for USDCHF

	1W	1M
CCY SIX Repo		
Constant c	16.10***	15.70***
t-stat	(7.23)	(8.58)
Observations	449	449
LIBOR		
Constant c	23.90***	33.10***
t-stat	(13.19)	(18.71)
Observations	2336	2336
OIS		
Constant c	44.00***	52.30***
t-stat	(15.16)	(19.47)
Observations	2236	2236

Table 9 shows the coefficient estimate and the respective t-statistics from regressing CIP deviations on a constant. The regression is run separately for CIP deviations calculated on the basis of CCY SIX Repo, LIBOR, and OIS rates, each for 1W and 1M maturities. The analysis covers the post-crisis period, which we define as running from July 31, 2007 to July 31, 2017. The coefficient estimates are shown in basis points. (***), (**) and (*) denote statistical significance (one-tailed) at the 1%, 5%, and 10% significance level, respectively. The t-statistics are depicted in parentheses below the coefficients.

Table 10: Deviations from CIP across maturities and instruments for USDCHF (p-values)

	1W vs. 1M
CCY SIX Repo	
Constant	71.80
LIBOR	
Constant	0.00***
OIS	
Constant	0.00***

Table 10 shows p-values from a paired t-test with unknown variance. According to the null hypothesis, the respective constant is equal in size for the 1W and the 1M regression in Table 9. The regression is run separately for CIP deviations calculated on the basis of CCY SIX Repo, LIBOR, and OIS rates, each for 1W and 1M maturities. The analysis covers the post-crisis period, which we define as running from July 31, 2007 to July 31, 2017. The coefficient estimates are shown in basis points. (***), (**) and (*) denote statistical significance (one-tailed) at the 1%, 5%, and 10% significance level, respectively. The t-statistics are depicted in parentheses below the coefficients.

References

Akram, F. Q., Rime, D., Sarno, L., 2008. Arbitrage in the foreign exchange market: Turning on the microscope. Journal of International Economics 76, 237–253.

Allen, W. A., Moessner, R., 2013. The liquidity consequences of the euro area sovreign debt crisis. BIS Working Papers No 390.

Avdjiev, S., Du, W., Koch, C., Shin, H. S., 2016. The dollar, bank leverage and the deviation from covered interest parity. BIS Working Papers .

Baba, N., Packer, F., 2009. Interpreting deviations from covered interest rate parity during the financial market turmoil of 2007-08. Journal of Banking and Finance 33, 1953–1962.

Baba, N., Packer, F., Nagano, T., 2008. The spillover of money market turbulence to fx swap and cross-currency swap markets. BIS Quarterly Review 1, 27–42.

Bank for International Settlements, 2016. BIS Triennial Central Bank Survey: Foreign exchange turnover in April 2016.

Borio, C., McCauley, R., McGuire, P., Sushko, V., 2016. Covered interest parity lost: understanding the cross-currency basis. BIS Quarterly Review pp. 45–64.

Brunnermeier, M. K., Pedersen, L. H., 2009. Market liquidity and funding liquidity. The Review of Financial Studies 22, 2201–2238.

Coffey, N., Hrung, W. B., Sarkar, A., 2009. Capital constraints, counterparty risk, and deviations from covered interest rate parity. Federal Reserve Bank of New York Staff Report .

Du, W., Tepper, A., Verdelhan, A., 2017. Deviations from covered interest rate parity. Working Paper .

Duffie, D., 1996. Special repo rates. Journal of Finance 4, 411–423.

Duffie, D., Stein, J. C., 2015. Reforming LIBOR and Other Financial Market Benchmarks. Journal of Economic Perspectives 29, 191–212.

European Central Bank, 2012. ECB Money Market Survey.

Fuhrer, L. M., Guggenheim, B., Schumacher, S., 2016. Re-use of collateral in the repo market. Journal of Money, Credit and Banking 48, 1169–1193.

Fuhrer, L. M., Müller, B., Steiner, L., 2017. The liquidity coverage ratio and security prices. Journal of Banking and Finance C, 292–311.

Mancini, L., Ranaldo, A., Wrampelmeyer, J., 2016. The Euro Interbank Repo Market. Review of Financial Studies 29, 1747–1779.

Mancini-Griffoli, T., Ranaldo, A., 2010. Limits to arbitrage during the crisis: funding liquidity contraints and covered interest rate parity. SNB Working Paper .

McGuire, P., von Peter, G., 2012. The dollar shortage in global banking and the international policy response. International Finance 15, 155–178.

Newey, W. K., West, K. D., 1987. A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. Econometrica 55, 703–708.

Pozsar, Z., 2017. Dollar funding after the storm. Creidt Suisse Global Money Notes .

Rime, D., Schrimpf, A., Syrstad, O., 2017. Segmented money markets and covered interest parity arbitrage. Preliminary Working Paper .

Sushko, V., Borio, C., McCauley, R., McGuire, P., 2016. The failure of covered interest parity: FX hedging demand and costly balance sheets. BIS Working Papers .

Swiss National Bank, 2015. Instruction sheet on collateral eligible for SNB repos.

Taylor, M. P., 1987. Covered interest parity: A high-frequency, high-quality data study. Economica 54, 429–438.

Wong, A., Leung, D., Ng, C., 2016. Risk-adjusted covered intrest parity: Theory and evidence. HKIMR Working Paper .