Collateral-adjusted CIP Arbitrages*

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Abstract

I show that an important no-arbitrage consistent but costly collateral rental yield contributes to about two-thirds of the standard CIP violations. I measure this yield using two approaches applied to short- and long-term CIP horizons. First, I assume that the yield is observable and proxy it with the difference between risk-free and overnight index swap rates between bilateral currencies. Second, I assume that the yield is unobservable and generate it using a model incorporating collateralization. Further, this yield appears to be related to global risks and intermediaries' frictions pointing to an important collateral transmission channel contributing to standard CIP violations.

JEL classification: C33, C4, F31, G1, E4, F31.

Keywords: CIP Violation, Collateral, FVA, Funding Rates, MtM (Mark-to-Market), No-Arbitrage.

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1 Introduction

Since the global financial crisis (GFC) in 2008, funding rates for derivative transactions have differed from those of cash markets, resulting in persistent cash-derivative bases that present arbitrage opportunities. A notable arbitrage is the violation of the covered interest rate parity (CIP), empirically measured by the bases on currency swaps performed using FX forwards (short-term) and cross-currency (xccy) swaps (long-term). These are referred to as the "xccy basis" (Du, Tepper, and Verdelhan, 2018). A currency swap is when two parties exchange loans of equal value but in different currencies.

After the GFC, a negative basis arose for lending US dollars against many G-7 currencies (see Figure 1). Thus, borrowing US dollars directly through the cash market became cheaper than through the currency swaps market, a surprising discrepancy for such a massive market. During the first half of 2019, the total outstanding national amount of currency swaps was $98 trillion, with an average daily turnover of $3.3 trillion (BIS, 2019). Further, the soundness of the no-arbitrage CIP condition holds economic importance globally, especially for market efficiency and international capital and trade flows.

Important literature about CIP establishes that there are CIP violations attributed to global risk factors and limits to arbitrage mainly due to intermediaries' frictions. These range from balance sheet constraints, regulation costs, funding costs, counterparty risk, finite capital, to FX hedging demand and market segmentation (summarized in Du and Schregner, 2021).

In this study, I reflect on what is a fair risk-free CIP violation after incorporating necessary collateralization features that remove counterparty risk in the over-the-counter (OTC) derivative markets. Thus, I depart from prior work that uses limits to arbitrage frictions and instead focus on no-arbitrage consistent collateral features to rationalize the apparent standard CIP violations.

The contributions are threefold. First, I propose and provide evidence that accounting for no-arbitrage-consistent but costly collateral wedges, which are institutional features of currency derivative contracts, may help resolve a big part of the apparent standard CIP violations across the maturity horizons. Collateral in currency swaps is time-varying (stochastic) due a mark-to-market (MtM) feature and arises mainly because of three institutional features: the collateral (1) is posted daily to cover the MtM of the currency swap, (2) is required to be posted predominantly in cash in US dollar, and, crucially, (3) is compensated at a non-market collateral rate that is different from the risk-free rate of return usually compensated for cash. Second, these wedges must be accounted for when pricing currency swaps and, therefore, when measuring CIP violations. I do this by quantifying and summarizing these wedges in a single metric called *collateral rental yield* using no-arbitrage formulations featuring collateralization. This yield is simply deducted from the apparent CIP violations.

Third, the results not only suggest that the apparent CIP violations mostly reflect collateralization wedges in the currency derivative contracts, but also point to an important collateral transmission channel through which some previously documented global risk factors and intermediaries' frictions work. These global macro risks include the strength of the US dollar. Based on this framework, the CIP is impacted by the strength of the US dollar because, according to the institutional features, the collateral is posted in US dollars, which becomes costly during US dollar appreciation.

Intermediaries' frictions include those imposed by quarter- and year-end, capital as well as leverage regulations. According to this study's framework, demand or supply for safe collateral assets and friction could, in turn, affect the proxies and modeling of the risk-free rate comprising the collateral rental yield. Additionally, the collateral's opportunity cost may deter intermediaries subject to high targets for return per unit of capital and liquidity from expanding their balance sheets with currency derivatives.

Otherwise, according to the framework, it is hypothetically possible for the collateral to be frictionless; however, this occurs only if such intermediaries' frictions do not affect the common risk-free rate (the rates proxying it) and if there is no residual counterparty credit risk in the derivatives traded. However, the results suggest that this is not the case and that some of the frictions enter the CIP violation somewhat via the collateral channel.

Furthermore, the results indicate that some residual counterparty credit and funding risks are priced into the aggregate currency derivative prices. This is evidenced by the relevant Libor-OIS spreads contributing to the CIP violation over and above the collateral costs. Such a result is expected since although the currency derivatives market is largely collateralized, in aggregate, it is not 100% perfectly collateralized.

Considering the collateral features of currency swaps is necessary for two reasons. First, since the GFC, the use of collateral agreements has gradually become substantial. For instance, according to the ISDA Margin Survey (2014), 91% all OTC derivative trades (cleared and non-cleared) were subject to collateral agreements at the end of 2013, compared with 30% in 2003. In the FX derivatives market, bulk of the transactions beyond 1-week tenor are collateralized. This is less so for transactions with less than 1-week tenor. Collateral mitigates the credit risk but also introduces additional collateral cash-flows and costs that cannot be ignored when performing CIP via currency swaps.

Second, trading a currency swap entails intense counterparty credit exposure, which comes with a great need for collateral posting. This is a consequence of the MtM feature since it is sensitive to not only interest rate fluctuations but also non-trivial FX rate fluctuations. FX rate fluctuations tend to be large in magnitude and more volatile, as well as affect currency swaps through the exchange of principal amounts in different bilateral currencies at maturity. Therefore, the collateral costs associated with currency swaps are much larger compared with, for instance, mere interest rate swaps.

Due to the presence of collateral in currency swaps, the CIP arbitrage measurement formula requires an adjustment to be consistent with no-arbitrage laws. The lending and borrowing rates ("discounting rates," "funding rates," and "investment rates") should be adjusted for a collateral rental yield. To do so, I build a forefront no-arbitrage pricing model for FX forwards and xccy swaps, featuring the institutional collateral features in the currency derivatives market. I propose two empirical approaches to estimate the collateral rental yield.

For a short-term horizon CIP, the first approach assumes that the collateral rental yield is observable. I proxy it with the difference between the risk-free rate and OIS rate[1] between bilateral currencies in the currency swap contract. To maintain simplicity, this study's framework is designed to feature the collateral rental yield in a risk-neutral way; hence, it features a hypothetical risk-free rate that is unique and prevailing in the market. In practice, however, there is substantial debate about the right single risk-free rate, and each has pros and cons.

I do not attempt to settle this debate; rather, I consider three proxies for a risk-free rate: the general collateral (GC) repo, BOX, and T-bill rates. GCs exhibit volatility due to the conditions in collateral markets and dealer balance sheet management.[2] The three-month T-bill rate often reflects default risk as well as convenience premiums.[3] The BOX rate from van Binsbergen, Diamond, and Grotteria (2019) is available only in US dollars. This is a risk-free rate implied by equity put-call parity prices. It purposefully excludes convenience premiums but can potentially be subject to idiosyncrasies of the underlying derivative instruments. Nevertheless, all three proxies lead to similar results. This is because my key purpose is to account for the sizable spread between the risk-free rate and collateral rate.

To further extend my results to the long-term maturity horizon CIP, I develop a second approach wherein I assume that the actual collateral rental yield is unobserved and generated from a simple no-arbitrage affine model. The model is estimated to fit a cross-section of market-implied collateral rental yields over time, extracted from data on xccy and interest rate swap prices, and it utilizes developed cutting-edge xccy swap pricing formulations. I then produce affine model-predicted collateral rental yields across tenors for each currency pair over time.

Both approaches lead to very similar results–the collateral rental yield explains a signifi-

[1]An OIS is an interest rate swap wherein the overnight rate is exchanged for a fixed interest rate. The OIS uses an overnight rate index—such as the FedFunds rate for the US dollar, Eonia rate for EUR, or Sonia rate for GBP—as the underlying rate for the floating leg, whereas the fixed leg is set at a rate agreed on by both counterparties/market for the tenor.

[2]A recent example is the December 2018 spike, which occurred because of a glut in the Treasury markets interacting with the year-end window-dressing of banks (Schrimpf and Sushko, 2019).

[3]For example, Krishnamurthy and Vissing-Jorgensen (2012).

cantly large portion (about two-thirds on average) of the apparent standard CIP violations across maturity horizons. Moreover, the results hold throughout the COVID-19 crisis (up to May 2020) as well as the tranquil period before it but after the GFC, but not during the GFC. It is noticeable that the collateral rental yield is far more relevant in the sample covering the period outside the GFC, which is consistent with collateralization becoming gradually more prevalent in the derivatives' market only in the aftermath of the GFC.

In practice, accounting for collateral costs in derivatives is linked to controversial cross-value adjustment metrics. Banks introduced these metrics after the GFC as part of their derivative management paradigm shift from hedging to balance sheet optimization. One metric is the funding value adjustment (FVA) discussed by Fleckenstein and Longstaff (2020) and Anderson, Duffie, and Song (2019). In general, FVA refers to an adjustment incorporated into the market price of a derivative to compensate the dealer for the cost of funding cash flows, including collateralization, throughout the life of the asset. The FVA has now become a standard in the industry. Due to widespread collateralization, the current main source of funding cost for the banks is dominated by the cost and benefit of the collateral (Ruiz, 2015).

Overall, the results point to an important collateral channel through which some of the previously documented intermediaries' frictions and regulations contribute to explaining the standard CIP violations. This helps reconcile the existing explanations in the CIP literature. This shows that the xccy bases are not arbitrarily determined, as may be the case given all plausible constraints. From a microeconomic point of view, they are fairly priced, reflecting the collateral costs in the context of the collateral-adjusted CIP, or the limits-to-arbitrage from the perspectives of those in favor of the constraints. From a macroeconomic point of view, the collateral costs in the currency derivatives market, which is one of the largest markets globally, are welfare deadweight losses giving rise to CIP violations. These violations, in turn, create distortions in the US dollar investment, funding, and hedging decisions of both financial and trade parties globally. Additionally, because the collateral costs are common among many derivative instruments, the commonality may extend to other asset class cash-derivative bases, which is a topic left for further research.

2 Related Literature

This study contributes and is related to three streams of literature. The first is the CIP violation conundrum, which triggered a wave of empirical studies in an effort to explain xccy bases and their determinants. During both the GFC and the European sovereign debt crisis, a common narrative emerged of foreign (mostly European) banks facing difficulties in borrowing dollar in short-term money markets and turning to FX swaps to cover for the dollar shortfall, as in Baba and Packer (2009a). Much of this early research explains the negative xccy basis as a temporary side effect of financial uncertainty and credit risk, while still connecting it to credit spreads (Baba and Packer 2009a, 2009b; Genberg, Hui, Wong, and Chung, 2008). Later studies pointed to funding liquidity issues and capital constraints (Genburg, Hui, and Chung, 2011; Coffey, Hrung, and Sarkar, 2009). Mancini-Griffoli and Ranaldo (2011) and Ivashina, Scharfstein, and Stein (2015) emphasize the effect of pullbacks in bank lending.

Starting in 2014, the basis grew tremendously even as financial markets enjoyed a period of relative calm and stability. Thus, initial explanations such as counterparty credit risk or temporary money market turbulence appeared less likely and credit risk-free arbitrage opportunities were identified in a seminal paper by Du, Tepper, and Verdelhan (2018). A second wave of studies emerged to re-evaluate the deviations from the CIP and offer new explanations, the predominant being balance sheet constraints.

Some sources attribute violations to diverging macroeconomic factors. Iida and Sudo (2018) and Du, Tepper, and Verdelhan (2018) link shifts in the level of CIP to diverging central bank policy. Sushko, Borio, McCauley, and McGuire (2016) identify shifts in the basis from imbalances in FX hedging demand. Few recent studies have pointed to differences in funding liquidity risks across currencies as the source for the basis (Rime, Schrimpf, and Syrstad, 2017; Wong and Zhang, 2018; Kuhler and Muller, 2019). This study differs by documenting that these macro factors play a role in the violations through the channel of the cost of US dollar collateral, especially during US dollar appreciation.

The second stream of literature investigates balance sheet constraints and the limits of funding supply arising from financial regulation. New non-risk weighted asset requirements, such as the LCR ratio or global systemically important bank (GSIB) score calculations, make balance-sheet intensive activities such as FX swaps more costly. Correa, Du, and Liao (2020) and Du, Tepper, and Verdelhan (2018) support this claim by documenting the strong premia for FX swaps present on end-of-quarter reporting dates. Cenedese, Corte, and Wang (2020) use transaction-level data to connect heterogeneity in dealer bank leverage ratio and xccy bases, whereas Avdjiev, Du, Koch, and Shin (2019) show that leverage constraint frictions driven by the strength of the dollar drive xccy bases. Augustin, Chernov, Schmid, and Song (2020) further document the role of financial intermediaries in the violation of the no-arbitrage conditions across term structures. This study takes a different approach by documenting that the CIP violations, and potentially other bases in the markets, to a large extend reflect institutional details of collateral in the derivative contracts and that the documented intermediaries' frictions mostly affect the CIP via this collateral transmission channel.

Ultimately, the studies so far do not offer conclusive explanations for both the emergence and persistence of the xccy basis. To reconcile these divergent explanations, the key to this pursuit is collateralization in derivatives, which has become central for pricing financial instruments post-GFC and is the third line of related literature. The first pricing effect of collateralization is to reduce counterparty credit risk (Brigo, Capponi, and Pallavicini, 2014; Fujii and Takahashi, 2012). The second pricing effect is to introduce additional stochastic collateral cash flows and costs, which can affect prices, as documented in the interest rate swap market (Johannes and Sundaresan, 2007) or index option markets (Leippold and Su, 2015). Moreover, collateralization can introduce complications due to imbedded "cheapest-to-deliver options" or netting (Fujii, 2010; Fujii and Takahashi, 2013).

The effects of collateralization lie within the growing family of cross value adjustments (xVAs), a set of new financial intermediaries' pricing considerations resulting from increased perception of counterparty risk management (and the credit risk, financial regulation, and collateralization that followed) since the GFC.[4] In recent years, more literature has sprung up regarding the legitimacy and proper definitions and derivations of various xVAs (see: Hull and White, 2012; Albanese, Caenazzo, and Crépey, 2017; Albanese and Crépey, 2017; Albanese, Andersen, and Iabichino, 2015; Ruiz, 2015; Albanese and Andersen, 2014).

In particular, FVA broadly incorporates collateralization. Recent research emphasizes FVA as a debt overhang problem, wherein profitability must exceed the firm's credit spread for shareholders to benefit from a particular trade, which has been proposed as an explanation for the CIP basis (Andersen, Duffie, Song, 2019; Fleckeinstein and Longstaff, 2019; Albanese, Chataigner, and Crepey, 2020). This study attempts to answer both unsolved questions regarding CIP, as well as further develop evidence on the effects of post-GFC collateral value adjustments.

3 Institutional Background: CIP and Collateralization

3.1 CIP

Based on the literature, the violation to the CIP is empirically measured by the xccy basis calculated using FX forwards (short-term) and xccy swaps (long-term) (Du, Tepper, and Verdelhan, 2018). An FX forward fixes the money to be transacted in the bilateral currencies at the start of the trade. In a xccy swap, two parties exchange interest payments on loans, usually 3-month Libor during the life of the swap, as well as the principal amounts at the beginning and end.

The textbook CIP condition states that the forward exchange rate is:

[4] Examples of XVAs include: (1) provisions for the credit or debt valuation adjustment (CVA), an adjustment subtracted from the mark-to-market (MtM) of a derivative position to account for the potential loss due to counterparty default, DVA, an adjustment added back to the MtM of a derivative position to account for the potential gain from the (insurer or contract writer) institution's own default. DVA is basically a CVA from the perspective of the other counterparty. If one counterparty incurs a CVA loss, the other counterparty incurs a corresponding DVA gain; (2) the capital valuation adjustment (KVA), the cost of holding regulatory capital for derivatives trading business, and (3) funding value adjustment (FVA) is an adjustment incorporated into the market price of a derivative to compensate the dealer for the cost of funding cash flows.

$$F_{t+1} = S_t \times e^{r^{\$}_{t+1} - (r^i_{t+1} + \underbrace{x^i_{t+1}}_{=0})} \tag{1}$$

where the spot S_t and the time $t+1$ forward F_{t+1} exchange rates are expressed as the price in (\$) - domestic currency (US dollar) for one unit of (i) - foreign currency (e.g., one EUR).

Moreover, in logs, the annualized continuously compounded forward premium is then equal to the bilateral currencies' annualized continuously compounded risk-free interest rates differential:

$$\ln \frac{F_{t+1}}{S_t} = f_{t+1} - s_t = r^{\$}_{t+1} - (r^i_{t+1} + \underbrace{x^i_{t+1}}_{=0}) \tag{2}$$

The CIP holds in the absence of arbitrage and is grounded in three key concepts. First, to prevent arbitrage opportunities, the xccy basis, x^i_{t+1}, should equal 0. Otherwise, there is a deviation from the CIP condition, which is measured by the annualized continuously compounded xccy basis: (expressed in foreign currency terms due to market convention)

$$x^i_{t+1} = r^{\$}_{t+1} - \left(r^i_{t+1} - (f_{t+1} - s_t)\right) \tag{3}$$

In the case of a negative basis, $x < 0$, assuming no counterparty risk and collareralization costs, a dollar arbitrageur can borrow the US dollar via the cash market domestically and lend them via the synthetic FX swaps market (0 net cash investment) and pocket x basis points per annum risk-free (see Figure 2 for standard CIP arbitrage cash flows).

Second, the lending and borrowing rates in each currency, $r^{\$}$ and r^i, should exist and be unique risk-free rates in the market. Third, the lending and borrowing rates should be accessible to any counterparty in the market. Implicitly, the CIP condition excludes the possibility of counterparty credit risk. Hence, measuring the CIP deviation requires explicit knowledge of the risk-free rates used to discount future cash flows in each currency and costless hedging of counterparty risk, which has proven difficult post-GFC.

3.2 The Risk-free Rate Conundrum

Finding rates to represent risk-free interest rates post-GFC is challenging. The empirical literature uses Libor rates as proxies. However, Libor rates are not risk free after the GFC because they misrepresent actual trading rates (no transaction costs, prone to distortion, incorporate credit risk, etc.). The next obvious candidates are OIS rates (for US dollar the FedFunds, for GBP the Sonia, for EUR the Eonia, etc., collectively called OIS rates), but they are uncollateralized money market rates and thus, not risk free. The rates of government bonds are affected by the regulation of risk management, taxation, embed sovereign credit risk, and receive convenience premiums (Krishnamurthy and Vissing-Jorgensen, 2012). GC repo rates could potentially work, but they exhibit volatility because of conditions in collateral markets and dealer balance sheet management. Additionally, data are incomplete or unavailable for some currencies and can include stale observations.

Practitioners usually assume no-arbitrage conditions and infer implied risk-free rates from the market for the derivative instruments they are trying to value, but those inferred rates are not readily tradable. An academic product of a similar exercise are the US dollar BOX risk-free rates extracted from the equity options market by Binsbergen, Diamond, and Grotteria (2019). These BOX rates are difficult to estimate for currencies other than the US dollar.

Because none of the discussed discount rates is unquestionably risk free, how can one make any of them default free? The answer is to introduce collateralization. However, eliminating credit risk via collateralization is not costless. Standard theory assumes that market participants can trade the risk-free discount rate, ignoring the intricacies of repo or collateralization markets. In practice, market participants are mindful that collateralization introduces costs and adjustments to discounting, forward prices, and implied volatilities, depending on the particularities of the collateral and its posting terms (Piterbarg, 2010). Black (1972), among others, considers an economy to be without a risk-free rate. However, traditional derivative pricing theory (e.g., Duffie, 2001) assumes the existence of such a unique risk-free rate as a matter of principle. Until the GFC, this assumption was plausible; however, not any more. An asset that is costlessly fully collateralized on a continuous basis is close to a risk-free asset (assuming no market segmentation or liquidity premiums, jumps in asset prices and intricacies of collateral posting and monitorining preventing full elimination of credit risk).

3.3 Institutional Features of Collateral

The use of FX forwards and xccy swap prices to measure CIP in the literature so far does not consider that these instuments are collateralized. Indeed, the measurement of the CIP should include costly non-market payments on collateral. Additionally, certain cash flows in xccy swaps are mechanical, such as the exchange of Libor rates, which are not risk-free rates, and hence should be taken into account (i.e., discount its mechanical impact) when measuring true CIP deviations. Otherwise, what the CIP deviation might be reflcting is simply risks of mechanical Libor cash flows.

The above is important especially since the use of collateral agreements is substantial nowadays. According to ISDA, by the end of 2013, 91% of all OTC derivatives trades (cleared and non-cleared) were subject to collateral agreements compared to only 30% in 2003. In the FX derivatives market, bulk of the transactions beyond 1-week tenor are collateralized, but less so are the transactions with very short maturities of less than 1-week. In the post-GFC world, swaps are generally collateralized under a Credit Support Annexe (CSA), in which one counterparty receives collateral from the other counterparty when the present value of the contract is positive and needs to pay the interest (collateral rate) on the outstanding collateral amount to the collateral payer. These CSAs regulate the collateral under the ISDA Master Agreement by defining the exact terms and conditions under which collateral is posted to mitigate counterparty credit risk.

Most of the transactions in the xccy derivatives market are bilaterally collateralized under standardized CSA terms that the collateral is rehypothecable but should be in the form of cash to cover the value of the daily MtM (ISDA Margin Survey, 2014). The base and most common choice of collateral currency is the US dollar if the currency pair is against the US dollar; thus, counterparties need to fund the US dollar denominated collateral on their xccy swap positions. Crucially, the collateral is compensated at a non-market collateral rate that is different from the risk-free rate of return. That rate is the CSA contract specified standard overnight (OIS) rate, which is usually lower that the risk-free rate.

Collateralization has profound effects on the valuation of financial instruments. Not only does it reduce the counterparty credit risk but it also changes the funding costs of derivative trades because of the introduction of stochastic intermediate collateral cash flows (Johannes and Sundaresan, 2007). The first point is readily apparent, however, the importance of the second point became acknowledged only after the GFC. Additionally, collateralization can reduce regulatory capital charges. However, this comes at the costs of higher collateral costs since in practice, it is not costless to eliminate counterparty credit risk, hence, collateral is costly for counterparties.

If a derivative contract is not fully collateralized, its funding cost is either directly linked to the Libor (if the counterparty is a part of the Libor panel banks) or to the counterparty's overall funding rate (Duffie and Singleton, 1999; Fleckenstein and Longstaff, 2020; and Andersen, Duffie, and Song, 2019). However, if the contract is fully collateralized by cash, the funding rate should be linked to the collateral rate provided by the overnight (OIS) rate of the collateral currency, which is specified in the CSA collateral agreement, a point illustrated further in Section 4.3.

4 Pricing Model

4.1 Assumptions

I present the simplifying assumptions employed in the framework of this study and describe a replication example of how collateralization maps to funding (discounting) rates. I assume that counterparties are risk-neutral, homogenous, and maximize profits in a fully competitive market. The implication is that the equilibrium-expected profits of the counterparties are zero.

I further assume continuous full collateralization by cash, meaning that counterparties post cash collateral in the full amount of the current MtM of the contract continuously at any point in time until expiration.[5] There is no remaining credit risk, known as “gap risk,” which is a sudden jump of the underlying asset and/or the collateral values at the time of counterparty default. A key assumption is the existence of a common hypothetical risk-free rate (money market account) and that is not affected by constraints and frictions, a point later relaxed and discussed in the empirical section.

4.2 Defining the Collateral Rental Yield

Collateral in the form of cash is easily invested or loaned out because it is rehypothecated. The cash collateral is default-free and remunerated with a risk-free rate if deposited in a money market account, such as a collateral account. However, in practice, the remuneration rate differs from the risk-free rate. Hence, I define the following important single-currency collateral opportunity cost wedge:

$$y = r - o \tag{4}$$

where r and o are the instantaneous *risk-free rate* and CSA specified *contractual collateral rate*, respectively. A common market practice, under a standard ISDA CSA, is for o to

[5] In practice, daily margining is common; hence, assuming continuous collateralization is a reasonable approximation.

equal the overnight (OIS) rate.

Economically, from the view point of a collateral receiver, the collateral wedge can be interpreted as a dividend yield because, for instance, the collateral receiver would place the cash collateral in a money market account earning a risk-free rate, r, while paying a contractual collateral rate, o, to the collateral payer, keeping the difference between the two. However, from the viewpoint of a collateral payer, it can be considered as collateral funding cost as the reverse is the case. Moreover, the return from a risky investment or borrowing costs from outside markets can be quite different from the risk-free rate. However, in this study's simplified framework, I use the risk-free rate as the net return after hedging these risks, assuming that hedging is costless.

For the xccy derivatives analyzed in this study, in terms of (\$) - domestic currency (US dollar) swapped for (i) - foreign currency where the former is used as the collateral, I define the following collateral rental yield:

$$y^{i/\$} = y^i - y^\$ \tag{5}$$

where

$$y^i = r^i - o^i \qquad y^\$ = r^\$ - o^\$$$

which represents the difference in collateral opportunity cost wedges between currency (i) and (\$). The above identity is applicable for the case when rates are deterministic and in a discrete single-period time setting. I will use this measure to analyze the short-term CIP violations throughout the paper. However, for the more realistic continuous time stochastic setting case, I need to adjust the above collateral rental yield for a change in measure between the currencies as:

$$y^{i/\$}(s) = E_t^{Q^i}[(y^i(s)ds] - E_t^{Q^\$}[y^\$(s)ds] = E_t^{Q^i}[(y^i(s) - y^\$(s))ds] \tag{6}$$

where $E_t^{Q^i}[\cdot]$ and $E_t^{Q^\$}[\cdot]$ are the time t conditional expectation under the risk-neutral measure of currency (i) and ($) respectivelly, where the money market account of each currency respectivelly is used as a numeraire.[6] Notice that I am changing the measure using the Radon-Nikodym density:

$$\frac{dQ^{\$}}{dQ^{i}}|_t = \frac{\beta_t^{\$} S^{(i/\$)}(0)}{\beta_t^{i} S^{(i/\$)}(t)} \tag{7}$$

where $S^{i/\$}$ is the spot FX rate in terms of the domestic currency ($) per unit of foreign currency (i). I will use the above measure for the collateral rental yield in analyzing the long-term CIP violations in the remainder of the paper.

4.3 Mapping Collateralization to Funding Rates

To develop an intuition for how the collateral rental yield, measuring collateralization wedges, is mapped into funding (discounting) rates when pricing collateralized FX forwards and xccy swaps, I first set a simple example for how a borrower evaluates their funding when issuing a collateralized versus uncollateralized debt and when the collateral for it is in a domestic versus foreign currency.

Because it is necessary to select a particular hedge (replication) funding policy to develop and evaluate an arbitrage-free pricing framework, that policy is based on similar collateralized FX, xccy, and bond instruments in this study. Additionally, for elementary treatment, I assume that interest rates are deterministic.

Consider that a riskless counterparty is borrowing funds by issuing a zero-coupon bond in a foreign currency, e.g. (€). As ilustrated in Panel A of Figure 3, if there is no collateral posted, the value of the issued bond at the time t is $D_t^{uncollat} = e^{-r_{t+1}^{€}}$. The standard replication of this position is for the issuer to deposit $e^{r_{t+1}^{€}}$ at a money market account earning a risk-free rate, wait to collect one unit at time $t+1$, and pay this unit back to the holder of the zero-coupon bond.

[6]

$$\beta_{\cdot}^{i} = exp(\int_0^i r^i(s)ds)$$

However, when collateral posting is required, the aforementioned replication is not applicable, especially when there is a collateral rental yield (i.e., when the replicator's contractual collateral rate, o, is less than the borrowing rate, r). As illustrated in Panel B of Figure 3, the issuer can replicate directly with the zero-coupon bond holder. Considering the issued collateralized zero-coupon bond is valued at $D_t^{€}$ and sold to the holder. The bond holder will require exactly $D_t^{€}$ in cash collateral; hence, the issuer will receive zero net proceeds. The collateral grows at the contractual collateral rate, $o_{t+1}^{€}$ and pays one unit to the holder of the bond at time $t+1$, which is the bond's payoff. Thus, the price of the zero coupon collateralized bond is $D_t^{€} = e^{-o_{t+1}^{€}}$.

Note that the funding (borrowing, discounting) rate has been transformed from the risk-free rate, r, to the contractual collateral rate, o, because the purchaser of the zero-coupon bond has effectively financed its purchase with the collateral from the issuer at the cost of the collateral rate. The above example illustrates why derivative OIS discounting is justified as the contractual collateral remuneration rate, o, is the overnight (OIS) rate, which is standard under the CSAs.[7]

When collateral posting is required in one currency, for instance, the domestic currency (\$), and the bond is issued in the foreign currency, (€), denoted $D_t^{€/\$}$ here, then the replication would involve an FX forward trade. As illustrated in Panel C of Figure 3, the issuer must exchange the (€) denominated $D_t^{€/\$}$ into currency (\$) at the spot FX rate, S_0, to post as (\$) collateral. This collateral will grow at the domestic currency contractual collateral rate, $o_{t+1}^{\$}$, which at maturity time will need to be exchanged for one unit of the foreign currency (€) performed using an FX forward (for simplicity, I use a riskless counterparty uncollateralized FX forward assuming that the risk-free rates are known in each currency). Hence, the replication would entail the following no-arbitrage break-even described above:

[7] However, if the contractual collateral rate is specified as Libor, then one should use Libor as the discounting rate for the contract, even if it is different from the risk-free rate.

$$\frac{D_t^{€/\$}}{S_t} \times e^{o_{t+1}^{\$}} \times F_{t+1} = €1 \tag{8}$$

where F_{t+1} is the $t+1$ maturing forward rate of currency ($) per 1 unit of currency (€). Because, in general, the no counterparty risk forward is $F_{t+1} = S_t \times e^{r_{t+1}^{€} - r_{t+1}^{\$}}$ the value of the issued zero coupon bond is:

$$\begin{aligned} D_t^{€/\$} &= e^{-o_{t+1}^{\$} - r_{t+1}^{€} + r_{t+1}^{\$}} \\ &= e^{-(r_{t+1}^{€} - y_{t+1}^{\$})} \\ &= e^{-(o_{t+1}^{€} + y_{t+1}^{€/\$})} \end{aligned} \tag{9}$$

which is consistent with no-arbitrage replication. Note that the issuer will need to subtract the ($) instantaneous collateral wedge, $y_{t+1}^{\$}$, when depositing the collateral at the risk-free money market account in ($) at the risk-free rate, $r_{t+1}^{\$}$, if replicating with a money market account. In other words, if replicating with the collateralized zero coupon holder directly, the issuer will need to add the xccy (€/$) instantaneous collateral rental yield, $y_{t+1}^{€/\$} = y_{t+1}^{€} - y_{t+1}^{\$}$, to the contractual collateral rate $o_{t+1}^{€}$.

4.4 Pricing a Collateralized FX Forward

Following the replication logic above, when a collateral posting is required in one currency, for instance the domestic currency ($), and when interest rates are deterministic, the FX forward in a one-period setting at time t is simply equal to the ratio of the foreign to the domestic collateralized zero coupon bonds (discount factors) scaled by the spot FX rate. Moreover, because the FX forward is required to be collateralized in the domestic currency, ($), then the foreign collateralized zero coupon bond (discount factor) is collateralized in ($):

$$F_{t+1} = S_t \times \frac{D_t^{i/\$}}{D_t^{\$}}$$
$$= S_t \times e^{o_{t+1}^{\$} - (o_{t+1}^{i} + y_{t+1}^{i/\$})} \quad (10)$$

Comparing the above collateralized FX forward pricing Eq. (10) with the textbook CIP Eq. (1), notice that that if the CIP is measured using OIS rates in each currency, then the so-called "OIS-based" xccy basis, x_{t+1}^{OIS}, is allowed to deviate from 0, and the deviation is simply equal to collateral rental yield, $y_{t+1}^{i/\$}$, embedded in collateralized FX forwards. This means that, consistent with no-arbitrage laws, the fully collateral-adjusted xccy basis, x_{t+1}^{adj}, should equal zero:

$$x_{t+1}^{adj} = \left[o_{t+1}^{\$} - (o_{t+1}^{i} - (f_{t+1} - s_t))\right] - y_{t+1}^{i/\$} = 0$$
$$= x_{t+1}^{OIS} - y_{t+1}^{i/\$} = 0 \quad (11)$$

where $(f_{t+1} - s_t)$ denotes the log forward premium obtained from the log of the forward and spot exchange rates.

The illustration is slightly more involved if the collateral posting and the collateral rental yield are stochastic, which, is the case in the framework of this study because of the continuous MtM-ing feature. However, it follows the same logic as above. To model such collateralization features in this case, I build on some of the features of frameworks such as Johannes and Sundaresan (2007) and Fujii, Shimada, Takahashi (2010a). The following subsections detail the risk-neutral no-arbitrage framework for pricing the xccy basis under MtM and full collateralization in stochastic case. The pricing framework depends on the following theorem:

Theorem 1. When the collateral is posted in foreign currency, (i), the present value of a fully collateralized derivative, h_t, in the domestic currency, $(\$)$, paying h_T at time T is:

$$
\begin{aligned}
h_t^{\$} &= E_t^{Q^{\$}}\left[e^{-\int_t^T r^{\$}(s)ds} \quad h_T^{\$} \quad e^{\int_t^T y^i(s)ds}\right] \\
&= E_t^{Q^{\$}}\left[e^{-\int_t^T o^{\$}(s)ds} \quad h_T^{\$} \quad e^{-\int_t^T [y^{\$}(s)-y^i(s)]ds}\right] \\
&= E_t^{Q^{\$}}\left[e^{-\int_t^T o^{\$}(s)ds} \quad h_T^{\$} \quad e^{-\int_t^T y^{\$/i}ds}\right] \qquad \square.
\end{aligned}
$$

where $E_t^{Q^{\$}}[\cdot]$ is the time t conditional expectation under the risk-neutral measure of currency (\$), where the money market account of currency (\$) is used as a numeraire. Derivation of this theorem is in Appendix A.

Applying Theorem 1, the price of an FX forward with $T-$maturity $F(T)$, in terms of domestic currency (\$) per unit of foreign currency (i), where the domestic currency (\$) is used as the collateral for the contract, is:

$$
\begin{aligned}
F^{i/\$}(T) &= S^{i/\$}(t) \times \frac{D^{i/\$}(t)}{D^{\$}(t)} \\
&= S^{i/\$}(t) \times \frac{E_t^{Q^i}\left[e^{-\int_t^T [o^i(s)+y^{i/\$}(s)]ds}\right]}{E_t^{Q^{\$}}\left[e^{-\int_t^T o^{\$}(s)ds}\right]}.
\end{aligned} \tag{12}
$$

where $S^{i/\$}(t)$ is the spot FX rate in terms of the domestic currency per unit of foreign currency and $D^{i/\$}(t)$ and $D^{\$}(t)$ are the foreign (collateralized in domestic currency) and domestic collateralized zero coupon bonds (discount factors) respectively.

4.5 Pricing a Collateralized Cross-Currency Swap Contract

Because the liquidity of FX forwards is limited to short-term tenors of less than one year, the literature uses xccy swaps to evaluate the CIP conditions for longer tenors because they are more liquid. Based on Du, Tepper, and Verdelhan (2018), the CIP deviation based on Libor (Libor-based CIP deviation) does not involve any calculations and is given by the spread on the xccy basis swap since the swap is viewed as a series of short-term FX forwards.

However, due to collateralization, the structure of a xccy basis swap differs from that of a series of FX forwards. Xccy basis swaps have a non-linear payoff in Libor interest and FX rates since they exchange Libor indexed coupons as well as full principal amounts at maturity in the bilateral currencies. The cash flows are then discounted at the contractual collateral remuneration rates (OIS) to present value. Consequently, the xccy basis is equal to zero only if the Libor and OIS rates in each currency are equal to each other. However, this does not mean that the CIP violation is zero. For this to hold, not only do the Libor and OIS rates must equal each other, but the also need be risk-free.[8]

In practice, Libor and OIS rates are dissimilar and are both uncollateralized rates. Hence, the xccy basis is naturally non-zero, and mechanically, partly reflects the dynamics of the particular Libors' index risk (e.g., credit, liquidity, etc.) and cash flows.

The pricing of a xccy basis swap involves going long a Libor-based loan in one currency (e.g. domestic currency leg), while simultaneously going short a Libor-based loan in a foregn currency (e.g. foreign currency leg) that is exchanged at the current spot FX exchange rate (market condition). Applying Theorem 1, the following is the price of a spot starting T_N- maturing xccy swap where the domestic currency, (\$), is used as collateral for the contract.

The present value of the domestic currency leg at time 0 is:

$$h_0^{\$} = -1 + D^{\$}(0, T_N) \sum_{n=1}^{N} \delta_n D^{\$}(0, T_n) E^{T_n^{\$}}[L^{\$}(T_{n-1}, T_n)] \tag{13}$$

where $D^{\$}(0, \cdot) = e^{-\int_0^{\cdot} o^{\$}(s)ds}$, δ_n denotes a day-count fraction for the period $[T_{n-1}, T_n]$, $E^{T_n^{\$}}[L^{(\$)}(T_{n-1}, T_n)]$ is the set of collateralized forward 3-month Libors at each fixed T_{n-1} and maturing at T_n in currency (\$), and $o^{\$}(\cdot)$ denotes a set of contractual collateral (OIS)

[8] If the counterparties are of Libor credit quality and do not have a collateral agreement, there will be no collateral adjustment. The xccy swap Libor-indexed cash flows will be discounted at the same Libor rates, the present value of each leg of the swap will be par, and a zero xccy basis will be observed, which does not necessarily imply that there are no violations to the strict CIP non-arbitrage conditions since the strict CIP requires discounting at risk-free rates rather than Libor rates.

zero-coupon discounting rates.

The present value of the foreign currency leg at time 0 is:

$$h_0^i \approx -1 + D^{i/\$}(0, T_N) + \sum_{n=1}^{N} \delta_n D^{i/\$}(0, T_n) E^{T_n^i} \left([L^i(T_{n-1}, T_n)] + x_N \right) \tag{14}$$

where $D^{i/\$}(0, \cdot) = e^{-\int_0^{\cdot} o^i(s) + y^{i/\$}(s) ds}$, x_N is the "xccy basis" swap price for a tenor-N xccy swap, and $D^{i/\$}(0, \cdot)$ includes the set of $y^{i/\$}(\cdot)$ collateral rental yields.[9]

Combining the two currency legs above, it is necessary also to further impose the following no-arbitrage market condition which essentially means that the present value of the Libor-based loan in the foreign currency must equal the present value of the Libor-based loan in the domestic currency when converted to the foreign currency at the spot FX exchange rate:

$$S_0 \times h_0^{\$} = h_0^i \tag{15}$$

which completes the pricing of a collateralized xccy swap, where the collateral is posted in US dollars ($). Figure 4 illustrates the cash flows of a collateralized xccy basis swap.

The xccy basis represents the fair market price for exchanging of US dollar Libor for foreign Libor. Alternatively, the OIS rate can be used instead of Libor, because one needs to compare apples to apples, i.e. OIS with OIS-based and not Libor-based xccy basis. Thus, effectively, one needs to parse out the Libor index risk from the price of the xccy swaps prices obtained directly from the market. This is easily done by re-calculating the xccy basis swap price using Eq. (13), (14), and (15) by replacing the coupon cash flows represented by the Libor index curves, $[L(T_{n-1}, T_n)]$, with coupon cash flows represented by extracted OIS index curves, $[o(T_{n-1}, T_n)]$, from OIS swaps data. With this, I create

[9]Note that I use $E^{T_n^i}[L^i(T_{n-1}, T_n) + x_N]$ instead of the appropriate $E^{T_n^{i/\$}}[L^i(T_{n-1}, T_n) + x_N]$. If there exists a liquid IRS market of foreign currency, i, but collateralized with a domestic currency, $ (e. g., EUR IRS collateralized in US dollar), I can extract the forward Libors as $E^{T_n^{i/\$}}[L^i(T_{n-1}, T_n)]$. However, this is typically a rare case, thus I approximate it by $E^{T_n^{i/\$}}[L^i(T_{n-1}, T_n)] = E^{T_n^i}[L^i(T_{n-1}, T_n)]$, which works only if there is a zero quadratic covariance between L^i and $y^{i/\$}$.

synthetically calculated OIS-based xccy basis swap prices.

Overall, the above pricing framework explains how the choice of the collateral currency (e.g., US dollar), the MtM collateralization itself, and the wedge between the non-market collateral remuneration rate and the risk-free rate introduce additional stochastic cash flows, discounted at different discounting rates, affect the price of FX forwards and xccy swaps.

5 Empirical Strategy

I obtain empirical estimates of the collateral rental yield, $y^{i/\$}$, embedded in the pricing of FX forwards in Eq. (10) and xccy swaps in Eq. (14) to evaluate the impact and contribution of the collateralization to the xccy basis. I use two empirical strategies and study both the short- and long-term horizons of the CIP violation; the first applies to the short-term OIS-based xccy bases and the second applies predominantly to the long-term synthetic OIS-based xccy bases calculated by replacing the Libor index cash flows with OIS index cash flows.

Every counterparty in the OTC market is inclined to reflect their own funding, counterparty credit risk, or investment conditions, and not the risk-free rate conditions. In the theoretical pricing model, I used the risk-free rate conditions to identify the cost of collateralization as frictionless and differing from the aforementioned costs or risk-based returns. However, empirically, this is effective only if the proxies chosen for the risk-free rate are truly reflecting the theoretical risk-free rate conditions, meaning they are not affected by any of the other mentioned conditions. Otherwise, since the return of a risky investment, counterparty, or borrowing costs from outside markets can be quite different from the theoretical risk-free rate, such conditions may produce heterogenous counterparty dependent derivative prices. They would be reflected in the aggregate prices as residual aggregate counterparty or funding credit risks.

Unlike in the simplistic theoretical model part, in the empirical part here, the residual credit or counterparty risk in the FX forward and xccy contracts' market is not ruled out since not 100% of the market is fully collateralized in practice, especially for the short-term deviations from the CIP. Therefore, I account and control for any remaining counterparty credit risk, as well as for other balance sheet and regulatory frictions that could affect the proxies used for the risk-free rate. This approach additionally allows me to establish evidence for an important collateral channel through which global risk factors, balance sheet constraints, and regulatory frictions documented in the literature so far, propagate and affect the CIP violations.

5.1 Observable Proxies For Collateral Rental Yield

In the first strategy, applied to CIP violations in the short maturity horizon calculated using OIS rates and FX forwards, I assume that I can construct observable proxies for the collateral rental yield using market-observable interest rates.

To identify a robust observable proxy for xccy collateral rental yield $y_n^{i/\$}$ in Eq. (5), I use three interchangeable proxies for the risk-free rate, r_n, and one proxy for the collateral rate, o_n, in each currency. I proxy the contractual collateral rate with the OIS zero rate since it is the standardized ISDA CSA contractual collateral rate used in the OTC derivatives market.

The first risk-free rate proxy is the GC repo rate denoted $r_{n,gc}$. This rate is collateralized, easily tradable, and transaction-based. In addition, because of regulatory and market efforts to reduce counterparty credit risk in interbank exposures, banks have also tilted their funding mix toward less risky sources of wholesale funding (in particular, GC repos). This is especially so to fund collateralized derivatives positions such as xccy swaps. Moreover, derivatives market reforms (such as the mandatory shift to central clearing of standardized OTC derivatives, and a move towards more comprehensive collateralization of OTC derivatives positions) have also increased the importance of funding with no credit risk using the GC market.

However, GCs exhibit volatility owing to conditions in collateral markets and dealer balance sheet management. A notable recent example is the December 2018 spike, which was because of a glut in Treasury markets interacting with banks' year-end window-dressing (Schrimpf and Sushko, 2019). Therefore, I would expect that the collateral rental yield proxy constructed using GCs as reference risk-free rates exhibits similar volatility related to conditions in collateral markets as well as dealer balance sheet management which are passed on to the FX and xccy derivative contracts traded. Additionally, data on GCs are also not available for some currencies, are incomplete, and can have stale observations.

Applying Eq. (5), the proxy for the collateral rental yield using GC repo rates rates is calculated as:

$$y_{n,gc}^{i/\$} = (r_{n,gc}^{i} - o_{n}^{i}) - (r_{n,gc}^{\$} - o_{n}^{\$}) \tag{16}$$

where n stands for $1m$ (1-week), $1m$ (1-month), and $3m$ (3-month).

The second alternative proxy for the risk-free rate is the 3-month T-bill rate for each currency denoted r_{tbill}. This rate is often criticized as potentially reflecting default risk as well as convenience premiums (Krishnamurthy and Vissing-Jorgensen, 2012). I use this proxy only for the 3-month maturity horizon analysis and it is calculated as:

$$y_{tbill}^{i/\$} = (r_{tbill}^{i} - o_{3m}^{i}) - (r_{tbill}^{\$} - o_{3m}^{\$}) \tag{17}$$

The third proxy, available only for the US dollar, is the 6-month BOX rate from van Binsbergen, Diamond, and Grotteria (2019). This rate is the interest rate implicit in the $S\&P$ 500 option box spread. It excludes convenience premiums; however, it could potentially reflect costs and frictions associated with holding and trading the underlying equity derivatives. Also, I use this proxy only for the 3-month maturity horizon analysis. It is calculated as:

$$y_{BOX}^{i/\$} = (r_{tbill}^{i} - o_{3m}^{i}) - (r_{BOX}^{\$} - o_{3m}^{\$}) \tag{18}$$

The above proxy is a combination of the foreign 3-month risk-free rate proxied by the foreign 3-month T-bill rate and the US 3-month risk-free rate proxied by the 6-month

BOX rate (since data on 3-month US BOX rate or foreign currency BOX rate was not available).

5.2 Unobservable Model-Based Collateral Rental Yield

The second strategy applies predominantly to long-term CIP violation measured using xccy swaps prices (apart from the 3-month horizon which is overlapping). I assume that the collateral rental yield is unobservable and obtain it from the market utilizing the developed no-arbitrage pricing model in Section 4. First, I extract it from prices of xccy, OIS, and interest rate swaps. Then, to give explicit no-arbitrage evolution, I estimate a simple Kalman filter latent factor affine model to fit the above extracted collateral rental yield's term structures. Finally, I produce time series data of model-predicted collateral rental yields across tenors in each currency pair.

I follow the curve extraction procedure described in Appendix B. I calibrate the forward OIS curve from the market OIS swaps and the collateralized forward Libor curve from the market interest rate, tenor, and OIS swaps. I then combine the collateralized forward Libor and OIS curves together with the market prices for the xccy basis, x_n, in the xccy swap pricing, Eq. (13) and (14), and evaluate the market condition with Eq. (15). This allows me to extract the only unknown, which is the term structure of the xccy collateral rental yield that was defined in Eq. (6) for each month and each currency pair in the sample. This measure entails the change of measure between the bilateral currencies reflecting the feature that the collateral is denominated in US dollars. As part of the extraction procedure, I also strip the term structure of the Libor-OISs of each currency.

This extraction procedure is novel to the CIP empirical literature and presents the particular collateral rental yield associated with holding a xccy swap position since it is extracted directly from xccy swap markets. In contrast, trying to infer the cost of collateral simply from interest rate swap markets would not consider the non-trivial FX spot rate risk which makes posting collateral bigger, thus would result in estimates of collateral costs that are constant and relatively small in magnitude compared to the real ones.

Affine Model: I fit a Kalman filter latent factor affine model to the term structures of the extracted collateral rental yield. The term structures include the monthly cross section of the 3-month, 1-year, 5-year and 10-year extracted zero rates over the sample period. I assume that their instantaneous short rate is a linear combination of three correlated latent state factors, denoted by z_1, z_2, z_3, as follows:

$$y_{AF}^{i/\$} = \sum_{i=1}^{3} z_i \tag{19}$$

Each of the state variables is governed by a set of stochastic differential equations that follow a Vasicek (1977) process:

$$\begin{aligned} dz_1(t) &= f_1(z_1, t) + \rho(z_1, z_j, t)dW_1(t), \\ &\vdots \\ dz_3(t) &= f_3(z_3, t) + \rho(z_3, z_j, t)dW_3(t). \end{aligned} \tag{20}$$

where $W_i(t)$ is a standard scalar Wiener process defined on $(\Omega, \mathcal{F}, \mathcal{P})$ for $i = 1, 2, 3$, whereas f_i represent the individual drift coefficients for each process and ρ_i's are the diffusion terms. Since there are three state variables, I allow their diffusions, ρ_i, to capture the covariance between them, i.e. between the various sources of uncertainty. I assume market completeness and no-arbitrage and let the pure discount bond for maturity T be an affine function of the three latent underlying risk factors, $P(t, T) = P(t, T, z_1, z_2, z_3)$.

The model is formulated in the state space and has two systems of equations. The first is the observed system of equations, which is the *measurement system*. This system represents the affine relationship between the zero coupons of the extracted collateral dividend yield and the state variables. The second is the unobserved system of equations, or the *transition system*. I use this state-space formulation to implement the model to recursively infer the unobserved values of the state variables (transition system), by conditioning on the observed extracted zero-coupon rates of the collateral rental yield(measurement system). As a final step, I use these recursive inferences to construct and maximize a log-likelihood function to find the optimal parameter set (see Appendix C for parameters solution derivation and Appendix D for model estimation and implementation). Finally, I produce model-predicted values of the collateral rental yield across the term structure for each currency, denoted $y^{i\$}_{n,AF}$.

The strength of this approach is in its simplicity and flexibility by allowing the collateral rental yield to depend on unobserved state factors. Moreover, the model allows me to achieve two important outcomes. First, to extend the analysis horizon beyond 3-months, for which I cannot observe any proxy for a risk-free rate. Second, to avoid taking a position on the appropriate proxy for the true risk-free rate, by simply assuming that the extracted collateral rental yield contains information about the market priced risk-free rate implied from the prices of risky securities.

6 Results

I first describe the data and then present the results and their implications for the alternative empirical estimates for the collateral rental yield.

6.1 Data

I focus on the G-7 currencies. These currencies are all against US dollars and are denoted by their abbreviations: Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), euro (EUR), British Pound (GBP), and Japanese yen (JPY). I use panel data for the 1-, 5-, and 10-year cross currencies, interest rates, tenors, and OISs. Additionally, I use data on 1-week, 1-month, and 3-month FX forwards and FX spot, ask, bid, and closing prices. I also obtain panel data on 3- and 6-month Libor and 1-week, 1-month, and 3-month GC and OIS rates for each currency. All of the above data, apart from the EUR GC repo rates obtained from BNP Paribas, are from Bloomberg. The sample period is from September 1, 2008, to May 31, 2020, covering both the GFC and the COVID-19 crises, as well as the tranquil period in between. GC repo rates from Bloomberg are obtained from Tullet Prebon, Swiss Stock Exchange, and the Bank of England.

I use the US dollars 6-month BOX rates from van Binsbergen, Diamond, and Grotteria

(2019) as well as 3-month T-bill rates from Bloomberg. These data are used as alternative proxies of the risk-free rates when constructing different observable measures for the 3-month collateral rental yields. I also obtain data on the leverage of security broker dealers from Adrian, Etula, and Muir (2014) (AEM) and on leverage and capital factors of bank holding companies from He, Kelly, and Manela (2017) (HKM) to investigate their covariation with the collateral rental yields. Appendix E provides further information on the data.

6.2 Collateral-Adjusted Deviations from CIP Across Maturity Horizons

There is a cross-sectional relationship between the collateral rental yield and its corresponding maturity standard OIS-based and Libor-based xccy basis. Figure 5 reports the mean xccy basis on the vertical axis as a function of the average collateral rental yield using different measures on the horizontal axis for the 2009–2020 period. The xccy basis is positively correlated with the collateral rental yield at the short- and long-term horizons. The relationship works particularly well for the model-predicted collateral rental yield, where the correlation with its corresponding maturity 3-month, 5-year, and 10-year xccy basis equals 92%, 86% and 93% respectively for G7 currencies against US dollars.

Moreover, estimating the collateral rental yield across different measures, I find a large reduction in the magnitude of CIP violations relative to measurement approaches that ignore collateral rental yield, that is, that ignore adjusting for costs of collateral. Table 1 provides the mean and standard deviation of the unadjusted versus collateral-adjusted CIP violations across tenors from 1-week to 10-year for the G-7 currencies since 2008. It reports these moments for the full sample excluding the crisis sub-periods ("Post-Crisis") and for a subset of crises (collectively "Crisis"). Notably, the model-based adjusted xccy basis, which is adjusted with the model-predicted collateral rental yield, is the most reduced, collapsing almost to zero across tenors, especially for the Post-GFC sample. The collateral adjustment is made on the synthetic OIS-based xccy basis that has already been parsed out of the Libor index risk to compare alike OIS-based measured xccy bases across tenors.[10]

In the Post-GFC tranquil sample period, the collateral adjustment to the short-term standard OIS-based xccy basis reduces the magnitude of the basis by about 12, 16, and 15 basis points for the 1-week, 1-month, and 3-month GC-adjusted xccy basis respectively, 10 basis points for the 3-month T-bill-adjusted xccy basis, 24 basis points for the 3-month model-based collateral-adjusted xccy basis. It even makes the BOX-adjusted collateral xccy basis positive by about 7 basis points. Additionally, the model-based collateral adjustment to the long-term synthetic OIS-based xccy basis reduces the magnitude of the basis by about 13, 20, and 30 basis points for the 1-year, 5-year, and 10-year respectively. Taken together, these results equate to between one-third to complete, or on average, across tenors, about a two-third reduction in the magnitude of the OIS-based CIP deviation due to collateral adjustment.[11]

However, during the Crisis sample period, the collateral-adjusted xccy basis is not much different from the standard OIS-based xccy basis for any measure apart from the BOX-based and model-predicted collateral adjustments. This indicates that the BOX and model-predicted based rental yields are capturing additional financial and economic stress factors present during crises. Nevertheless, the results suggest that in crisis times, collateralization becomes of secondary importance for xccy swap prices.

[10]The model-based collateral adjusted xccy basis, $x^{adj}_{n,AF}$, is adjusted using the affine model-predicted collateral rental yield, $y^{i/\$}_{n,AF}$ from Eq. (19), on the a calculated synthetic long-term OIS-basis xccy swap price, x^{OIS}_{n}. I calculate this long-term OIS-basis xccy swap price price using identities in (13), (14), and (15) by replacing the coupon cash-flows represented by the Libor index curves with coupon cash flows represented by extracted market OIS index curves from OIS swaps data.

[11]In the table, using Eq. (11), the GC-adjusted collateral xccy basis, $x^{adj}_{n,gc}$, is re-calculated using the maturity matched proxy collateral rental yield utilizing GC rates, $y^{i/\$}_{n,gc}$, from Eq. (16) where n stands for $1w$ (1-week), $1m$ (1-month), and $3m$ (3-month). The T-bill-adjusted collateral xccy basis, x^{adj}_{Tbill}, is re-calculated using the proxy collateral rental yield utilizing 3-month T-bill rates, $y^{i/\$}_{Tbill}$ from Eq. (17), and the BOX-adjusted collateral xccy basis, x^{adj}_{BOX}, is re-calculated using the proxy collateral rental yield utilizing foreign 3-month T-bill and US 6-month BOX rates , $y^{i/\$}_{BOX}$, from Eq. (18).

6.3 Short-Term Collateral-Adjusted Deviations from CIP

Table 2 shows results from panel regressions of the short-horizon OIS-based xccy basis, x_{3m}^{OIS}, on each of the three alternative proxies for the collateral rental yield respectively for 1-week, 1-month, and 3-month tenors and other covariates from the empirical literature. These include specifications where all variables are in levels (Panel A) and in changes (Panel B). Because the data for the proxy variables of the collateral rental yield might be stale[12], I consider the results in levels and not just changes. For specifications in levels, stationarity is ruled out (based on augmented Dickey-Fuller and other stationarity tests).

If the proxy collateral rental yield measures collateral costs effectively and the FX forward market in aggregate is fully collateralized, Eq. (11) suggests a slope coefficient of 1 and an R^2 of 1. From Table 2 Panel A, each proxy's slope coefficient is statistically significant (at 1%) and close to 1 (apart for the 3-month horizon), and the R^2 are large.

The collateral rental yield between the bilateral currencies is associated with more, almost one-for-one, negative xccy basis, which is economically meaningful. In particular, for the 1-week and 1-month tenors, the coefficient estimate for the GC-based collateral rental yield (in columns 1 and 3 of Table 2 Panel A) implies that the marginal impact of one basis point (0.01%) decrease in the collateral rental yield and is associated with 1.1 and 1.4 basis point decrease in the xccy basis respectively. Results for the 3-month basis are qualitatively similar but smaller in magnitude. As expected, the collateral rental yield proxy's magnitude declines as the tenor of the xccy increases. This is because in practice, institutions manage their collateral needs dynamically over the life of the derivative, and hence the collateral cost proxies applied to the longer term do not capture this dynamic well.

Moreover, the coefficient estimates for the collateral rental yield are similar in magnitude between the three proxies. Therefore, the measures (and proxies) used for the collateral rental yield are robust and are not sensitive to the choice of the risk-free rate proxy, alleviating the potential criticism of identifying a post-GFC risk-free rate as discussed in

[12] Especially for GC rates, for example.

the literature. Remarkably, for all specifications, all proxies of the collateral rental yield also survive the inclusion of other factors documented to contribute to the variation of the xccy basis in the literature.

Residual credit or counterparty risk in the FX forward contracts' market is not ruled out. Formally, the counterparty default risk explanation of CIP deviations relies on cross-country differences in the credit worthiness of different Libor panel banks. According to Du, Tepper, and Verdelhan (2018), looking at the other extreme, of having no collateralization in the market and assuming no-arbitrage, the xccy basis should equal the difference between credit risk spreads (above the theoretical risk-free rate) in the foreign currency and US dollar Libor panels. In Table 2 Panel A, the Libor-OISs spreads are persistently significant across specifications. The results in changes in Table 2 Panel B show similar results and conclusions.

An important caveat is how well the Libor-OISs spread can represent the counterparty credit risks involved in xccy prices, in other words, how applicable Libor is for participants to borrow on an unsecured basis for xccy swaps. Admittedly, the Libor-OIS spread is not a perfect measure of the risks for the xccy market. First, the Libor scandal is well known, and therefore its reliability as a measure of the cost of funding accessible by banks in general seems questionable (Hou and Skeie, 2014). Second, there is a considerable difference in the composition between the Libor and xccy markets. The Libor market mainly consists of banks, while the xccy swaps market comprises of a wide range of financial and non-financial institutions, including banks, insurers, investment managers, hedge funds, and large corporations. It is clear, therefore, that most of the xccy market participants are unable to access funds at Libor on an uncollateralized basis. As a result, the risks are likely to be underestimated. Yet, most likely, if counterparty risk is very high, parties will opt for full collateralization. Therefore, the spread is still arguably the best available measure that can serve as a reasonably good approximation of residual counterparty risks or collateralization presence in the market.

Furthermore, to obtain evidence of residual regulatory constraints, I test whether short-horizon CIP deviations are more pronounced at the end of the quarters versus any other point in time in a manner similar to Du, Tepper, and Verdelhan (2018). $Qend$ is an indicator variable that equals 1 if the date is within 6 days of the quarter end, and 0 otherwise and $Yend$ is an indicator variable that equals 1 if the date is in the last month of the year, and 0 otherwise. In Table 2 Panel A, the quarter-end coefficient is negative and significant, indicating larger CIP deviations. It is -25 basis points for the 1-week and -8 basis points for the 1-month horizon, but it is not significant for the 3-month horizon. This is expected since a 3-month forward contract always shows up in a quarterly report regardless of when it is executed within the quarter. Additionally, the year-end coefficient is also significant over and above the quarter-end for all maturities, including the 3-month horizon. The effect is quite large, -40 basis points for the 1-week and -51 basis points for the 1-month horizon, however, as the maturity increases the magnitude of this effect becomes smaller.

The result is consistent with the key role of banks' balance sheets on quarter and year-end reporting dates. I do not discern which part of the regulation matters most, but the result suggests that banking regulations driving the quarter and year-end anomalies in the xccy markets, driven by *window dressing* for better regulatory capital ratios, are consistent with other asset markets, for example, the quarter-end sharp decline in the US Triparty repo volume (Munyan, 2017) and the quarter-end spike increases in the GC repo rates. These GC rates are used in one of the proxies for the collateral rental yield.

The strength of the US dollar is also significant for the xccy basis for the 3-month horizon in Table 2 Panel A. According to this study's framework, this is a result of the need to collateralize the daily MtM, chiefly in US dollar. Greater US dollar strength is associated with higher cost of collateral and more negative xccy basis. The trade weighted US dollar index[13] created by the US Federal Reserve System, is significant across specifications apart

[13]The trade-weighted US dollar index is used to determine the US dollar's purchasing value and summarize the effects of dollar appreciation and depreciation against foreign currencies. Trade-weighted dollars give importance, or weight, to currencies most widely used in international trade, rather than comparing the value of the US dollar to all foreign currencies. EUR is, by far, the largest component of the index, making up almost 58% (officially 57.6%) of the basket. The weights of the rest of the currencies in the index are

from in the 1-week and 1-month tenors. The longer the tenor, the more prevalent the collateralization, the higher the counterparty exposure intensity, and hence the more the currency of the collateralization matters. While Avdjiev, Du, Koch, and Shin (2019) link the broad dollar index to the xccy basis through a cross-border bank lending channel, my framework connects the two via the need to post US dollar-denominated collateral channel. Additionally, the forward FX bid-ask spread liquidity frictions also seem to affect the OIS-based xccy basis, albeit not consistently across tenors.

Note that, based on the framework, the strength of the US dollar should affect the xccy basis only via the collateral channel and thus should be absorbed by the collateral rental yield measure. Therefore, it should not show up as significant here separately. However, for the short-term basis analysis, the proxies for the collateral rental yield do not entail the change of measure between the bilateral currencies reflecting the feature that the collateral is denominated in US dollars. For the long-term xccy basis analysis next, the model-predicted collateral rental yield does entail the change of measure, therefore the strength of the US dollar effect is seen only via the collateral channel embedded in the collateral rental yield.

Furthermore, Table 3 presents results from a difference-in-difference panel regression of the OIS-based xccy basis on an interaction with a dummy, denoted $Post - Crisis$, indicating 1 for the sample period from January 1, 2010 to May 31, 2020 excluding two crisis periods for which it is indicating 0. Those crisis periods are the GFC, from August 2008 - December 2009, and the Covid, from March 2020 - May 2020 (subsamples are similar to Du and Schregner (2021)).

Apart from the collateral rental yield proxy using BOX rates, the proxies calculated using GC and T-bill rates are significant and important in magnitude only during the tranquil post-crisis times as evident by their significant coefficients on the interaction with the Post-Crisis dummy. However, the same are not significant during crisis periods. This suggest that the collateral rental yield is not very relevant in crisis times when many other

JPY (13.6%), GBP (11.9%), CAD (9.1%), SEK (4.2%), and CHF (3.6%) (Investopedia, 2019).

factors might be responsible for creating dislocation and mispricing in the in the xccy basis market, and that collateralization matters more when conditions normalize. The results further support that the BOX-based rental yield, just like the model-predicted rental yield analyzed next, most likely captures additional factors reflecting financial stress present mainly during crises.

In sum, the collateral rental yield is significant and accounts for, on average, about two-thirds of the short-term standard OIS-based CIP deviations, regardless of the choice of proxy for the risk-free rate for each of the alternative measures. The results also suggest that, in crisis times, collateralization becomes of secondary importance for xccy basis prices.

6.4 Long-Term Collateral-Adjusted Deviations from CIP

Most xccy basis swaps traded in the market are Libor-based. Combining a Libor-based xccy basis swap with other swaps such as Libor-OIS swaps in each bilateral currency allows one to customize the resultant swap to obtain an OIS-based xccy basis swap. This will parse out the mechanical Libor-index risk embedded in the prices of Libor-based xccy basis swaps to make appropriate CIP violation evaluations that are also consistent across tenors.

To see the contribution, Figure 6 plots the mechanical Libor-OISs spread between the currencies versus the affine model-predicted collateral rental yield next to the prices of standard Libor-based xccy basis contract market prices for the 3-month, 1-year, 5-year, and 10-year tenors over time. Observe that, historically, a significant portion in the variation of the Libor-based xccy basis swap price comes from the variation in the collateral rental yield rather than the Libor-OISs differential. However, the contribution composition is time varying and different for different currency pairs and tenors. Additionally, Figure 7 shows the term structures of the model-predicted collateral rental yield next to its corresponding horizon Libor-based xccy basis for several dates. The two can have upward sloping or inverted curves and generally exhibit similar term structures. However, their magnitudes do not match in levels completely since the collateral rental yield is often narrower than the Libor-based xccy basis.

I further analyze the CIP deviations appropriately and in a consistent manner across tenors while avoiding contamination from mechanical Libor-indexed cash flows. I do so by parsing out the Libors-index risk from the price of the Libor-based xccy swap prices obtained directly from the market. I calculate a synthetic OIS-based xccy swap price as described earlier. OIS-based xccy swaps have been traded directly in the market, although far less frequently and only on a few currency pairs and maturities. To overcome this shortcoming, I therefore create them synthetically.

Figure 8 plots the synthetic OIS-based xccy swap basis against each of the model-based collateral adjusted xccy swap basis for each of the 3-month, 1-year, 5-year, and 10-year tenors for each currency pair.[14] Observe that, across the term-structure, the collateral-adjusted xccy basis reduces almost entirely to zero across the tenors, although the reduction is more pronounced for the shorter rather than the longer horizon (e.g. 3-month than the 10-year).

Formally, Table 4 presents panel regression results from regressing the synthetic OIS-xccy swap basis on the model predicted collateral rental yield, $y^{i/\$}_{n,AF}$, for 3-month up to 10-year tenors and other factors from the empirical literature. It includes specifications wherein all variables are in levels (Panel A) and in changes (Panel B).

If the model predicted collateral rental yield measures collateral costs effectively and the xccy basis swaps market in aggregate is perfectly and fully collateralized, the framework suggest a slope coefficient of 1 and an R^2 of 1 (because the synthetic xccy swaps are OIS-based). For each horizon in Table 4 Panel A, the model-predicted collateral rental yield coefficient is close to 1 and statistically significant. The collateral rental yield between the bilateral currencies is associated with more negative xccy basis, which is economically meaningful. Moreover, the R^2 are quite large, ranging between one-third and 85%. Notice that, beyond 1-year, the explanation of the CIP violation increases as the horizon increases. Xccy basis swaps exchange principal amounts in different bilateral currencies at maturity,

[14]The model-based collateral adjusted xccy basis is adjusted using the affine model-predicted collateral rental yield, $y^{i/\$}_{n,AF}$ from Eq. (19), on the a calculated synthetic long-term OIS-basis xccy swap price, x^{OIS}_n.

and thus, their MtM is sensitive to one more non-trivial source of risk fluctuations, the FX rate fluctuations, which are quite volatile. Therefore, the MtM, as well as the need to post collateral, is large in magnitude, is more volatile, and increases with the tenor of the xccy swaps. Collateralization becomes more important and binding the a longer tenor swap.

The remaining contribution to the variation in the xccy basis, only for the tenors beyond 1-year, is due to the Libor-OISs spread potentially because of residual counterparty credit risk (not related to mechanical Libor cash flows) since the xccy basis swaps market, although largely collateralized, is not 100% collateralized.

Note that, unlike the result in the short-term basis analysis using observable proxies earlier, the strength of the US dollar does not have an independent contribution to the xccy basis here. This is likely because the model-predicted collateral rental yield entails a change of measure between the bilateral currencies reflecting the feature that the collateral is denominated in US dollars. Therefore, the effect from the US dollar is absorbed in the collateral rental yield and affects the xccy basis via this collateral transmission channel. No other factor, including the regulatory year-end, leverage, and capital factors, is persistently related to the long-term synthetic OIS-based xccy basis across the tenors.

In sum, the above analysis indicates that the model-predicted collateral rental yield is significant and accounts for about two-thirds of the apparent long-term OIS-based CIP violations on average across tenors. The results in changes in Table 4 Panel B show similar results and conclusions. Compared to the analysis using proxied collateral rental yields, the results using model-based collateral yields indicate that the intermediaries' frictions and the strength of the US dollar do not have independent effects on the CIP, suggesting that they possibly operate via the collateral channel, which I investigate in more detail next.

6.5 Global Risks, Intermediaries' Frictions, and The Collateral Channel

The literature has related the xccy basis to global risks and frictions facing intermediaries. To understand if there is evidence that these risks and frictions affect the xccy basis via a collateral transmission channel, Table 5 shows panel regression results from regressing the collateral rental yield on several counterparty and global risk proxies as well as on intermediaries' frictions. In particular, I examine the covariation of the various collateral rental yields with the regulatory year-end reporting constraints, the leverage of broker dealers factor from AEM, the leverage and capital factors of bank holding companies from HKM, the measures of US dollar risks, and the counterparty credit and funding risks.

In the specification in levels in Panel A, consistent with the key role of banks' balance sheets on year-end reporting dates, I find that all collateral rental yields, except the T-bill and BOX-based ones in columns (2) and (3), are statistically significant and systematically larger for contracts that cross year-end reporting dates. The collateral is on average 6 basis points more expensive on year-end across tenors. Apart from the 3-month GC and T-Bill-based collateral rental yield, the HKM regulatory leverage and capital factors are significant across measures, indicating that leverage and capital regulation affects collateral funding costs (the AEM leverage factor was tested and because it was insignificant was removed due to limited number of quarterly observations).

Moreover, the US Libor-OISs spreads are persistently significant across specifications, except for the GC-based collateral rental yield. This indicates a residual counterparty credit risk reflected in the Libor panel banks' risk captured in the proxies or in the model for the collateral rental yield due to imperfections in proxying the theoretically true risk-free frictionless rate.

The result that the collateral rental yield is related to proxies for intermediaries' frictions imposed by counterparty and funding constraints, leverage, or capital regulation is not surprising. Based on this study's framework, the collateralization is rationalized, developed, and implemented in a frictionless risk-neutral setting, assuming that every counterparty in the market can fund at a common risk-free rate and thus set as benchmark. However, the caveat is that, in practice, there is no single risk-free rate, the market is not 100% collateralized, and there are inevitable regulatory frictions. Additionally, the proxies used for the risk-free rate are imperfect. Therefore, the analysis suggests that it is plausible that the collateral is subject to frictions that are transmitted to other asset prices relying on that collateral, such as xccy basis swap prices.

Moreover, the results that the collateral rental yield covaries strongly with the strength of the US dollar, in line with the framework due to the need to post US dollar collateral, is supported here empirically with the significant coefficient on the US factor across measures except for the GC and T-bill-based proxies. Additionally, the log FX volatility and exchange rate, the forward FX bid-ask spread liquidity frictions, and the global risks measured by the VIX volatility index also seem to affect the collateral rental yield, albeit not consistently across tenors. The results in changes in Table 5 Panel B show similar results and conclusions.

Overall, the collateral rental yield persistently covaries with the measures of global risk, residual counterparty credit and funding risk and intermediaries' regulatory frictions. This points to a collateral transmission channel affecting the prices of the derivative contact prices used to perform the CIP, which in essence, limits theoretical arbitrages.

7 Conclusions

In this study, I introduce and implement costly collateralization to short- and long-term violations of the CIP no-arbitrage conditions. Such collateral considerations drive the opportunity costs associated with collateral investment and funding. Taken together, the empirical results suggest that collateralization details in derivative contracts are an important and persistent factor contributing (about two-thirds on average) to the violations of the standard CIP conditions. Due to the presence of collateral when trading FX forwards and xccy swaps, the CIP arbitrage measurement formula requires an adjustment for collateral wedges and currency to be consistent with no-arbitrage laws.

Furthermore, the results suggest an important collateral channel through which some of the previously documented global risks and intermediaries' frictions operate and contribute to explaining the standard CIP violations. This helps reconcile the existing explanations in the CIP literature and clarifies the pricing and risk management of CIP trades for market participants. Finally, because the collateral rental yield is common among many derivative instruments, one should expect a commonality among other asset class cash-derivatives bases, which is a topic left for further research.

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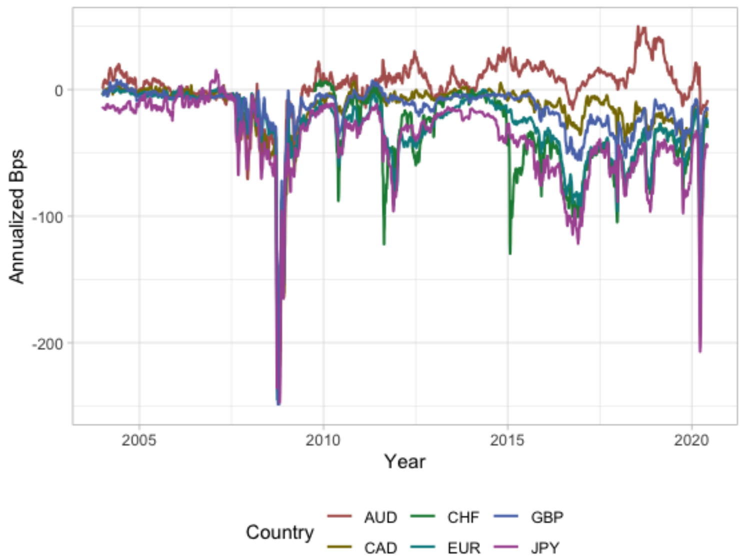
Figure 1: Historical Behavior of the Xccy Basis for G7 currencies against the US dollar. The countries and currencies are denoted by the abbreviations: Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), euro (EUR), British Pound (GBP), and Japanese yen (JPY).

Panel A: Short-Term OIS-Based Deviations from CIP

This figure plots the 7-day moving averages of the 3-month OIS-based xccy basis measured in basis points, for G7 currencies. The OIS-based xccy basis is calculated as: $o^{\$}_{t,t+1} - (o^{i}_{t,t+1} - \frac{1}{n}(f_{t+1} - s_t))$, where $o^{\$}_{t,t+1}$ and $o^{i}_{t,t+1}$, denote the US and foreign 3-month OIS rates and $(f_{t+1} - s_t)$ denotes the forward premium obtained from the forward and spot exchange rates. The CIP implies that the basis should be zero.



Panel B: Long-Term Libor-Based Deviations from CIP

This figure plots the 7-day moving averages of the 5-year Libor-based xccy basis measured in basis points, for G7 currencies, which is obtained from xccy basis swap contracts directly.

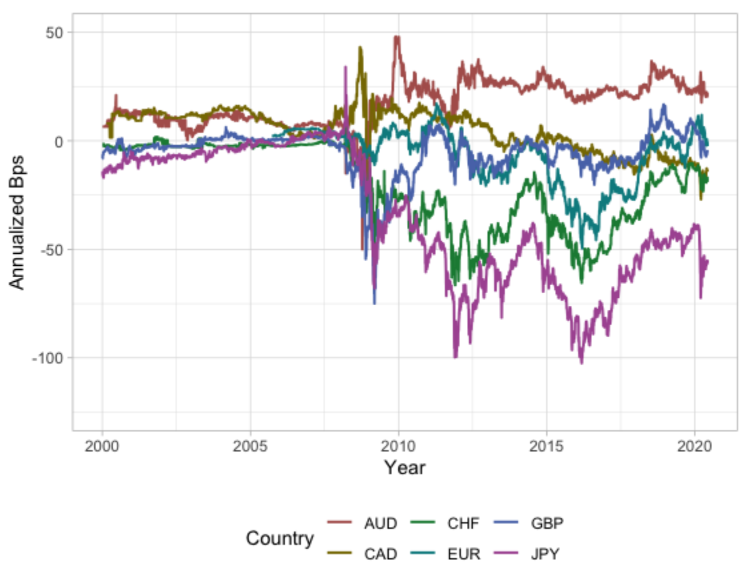


Figure 2: Cash Flow Diagram for Standard CIP Arbitrage in US dollars.
This figure plots the cash flow exchanges of an arbitrageur trying to profiting from a negative cross-currency basis ($x_{t,t+1} \leq 0$) between the euro and the US dollar not facing collateralization in US dollars. To arbitrage the negative standard OIS-based cross-currency basis, the US dollar arbitrageur will borrow S_t US dollars at the interest rate $o^{\$}_{t,t+1}$, convert and will lend 1 euro at the interest rate of $o^{€}_{t,t+1}$, and simultaneously will sign a non-collateralized forward contract at date t. There are net zero cash flows at time t. At date $t+1$, the arbitrageur will receive $e^{o^{€}_{t,t+1}} \approx (1 + o^{€}_{t,t+1})$ euro, and convert them into $e^{o^{€}_{t,t+1}} F_{t,t+1}/S_t \approx (1 + o^{€}_{t,t+1}) F_{t,t+1}/S_t$ US dollars thanks to the forward contract. At time $t+1$, the arbitrageur repays her debt in US dollars and is left with a profit equal to the negative of the cross-currency basis $x_{t,t+1}$. Essentially, the arbitrageur goes long in the euro and short in the US dollar loan, with the euro cash flow fully hedged by the non-collateralzied forward contract.

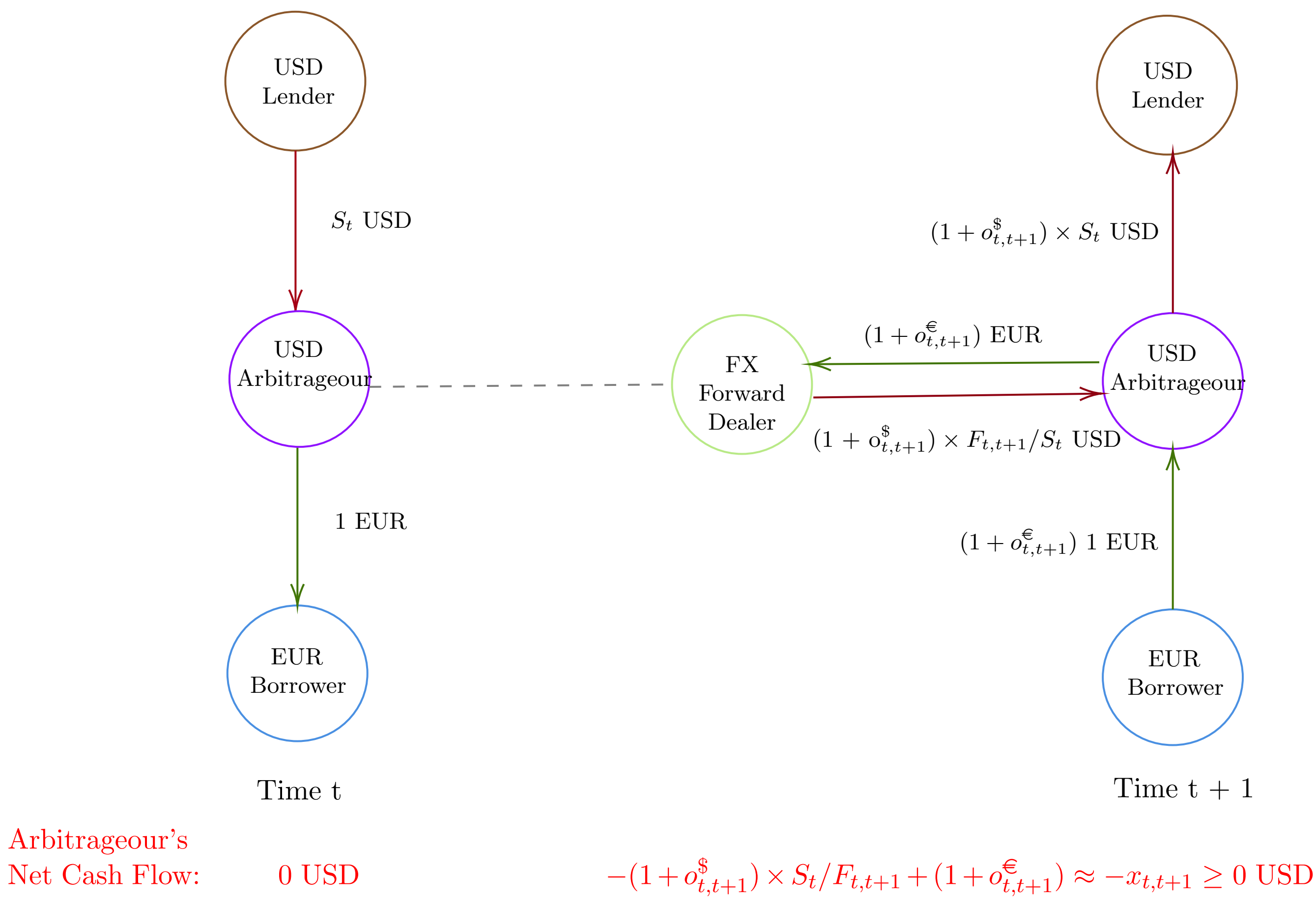
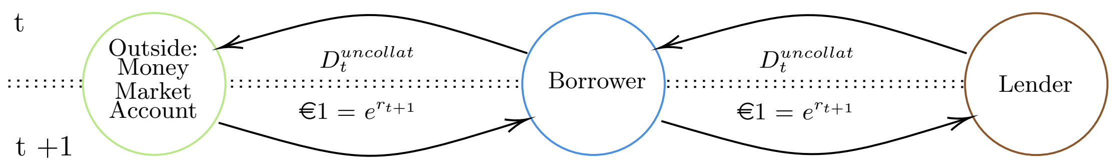


Figure 3: No-arbitrage replication cash flows of a Borrower (Issuer) of a Collateralized Zero Coupon Bond

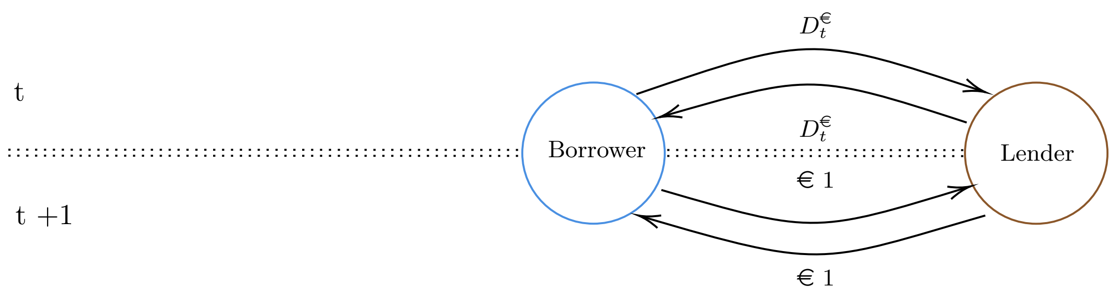
This diagram illustrates the cash flows of a non risky counterparty issuer associated with issuing a zero coupon (ZC) bond that is not collateralized ($D_t^{uncollat}$) in Panel A, a zero coupon bond that is collateralized in the same currency, €, of the issued bond itself ($D_t^{€}$) in Panel B, and a zero coupon bond that is collateralized in a different currency, \$, than the bond itself ($D_t^{€/\$}$) in Panel C. For simplicity interest rates are assumed to be deterministic. D_t denotes the present value of the collateralized zero coupon bonds in either of the currencies. o_{t+1} is the collateral rate in either of the currencies, while $y_{t+1}^{€/\$}$ is the collateral rental yield, which is equal to difference between each of the individual currencies collateral rental yields, $y_{t+1}^{€/\$} = y_{t+1}^{€} - y_{t+1}^{\$}$.

Penel A: No-Arbitrage replicating strategy when borrowing by issuing a ZC bond in € that is not collateralized



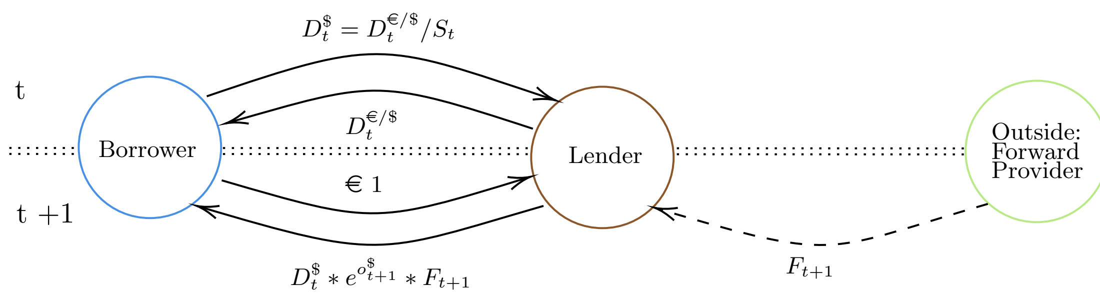
No-arbitrage brake-even present value of ZC bond: $D_t^{uncollat} = e^{-r_{t+1}}$

Penel B: No-Arbitrage replicating strategy when borrowing by issuing a ZC bond in € that is collateralized in the same currency €



No-arbitrage brake-even present value of ZC bond: $D_t^{€} = e^{-o_{t+1}}$

Penel C: No-Arbitrage replicating strategy when borrowing by issuing a ZC bond in € that is collateralized in another currency \$



No-arbitrage brake-even present value of ZC bond: $D_t^{€/\$} = e^{-(o_{t+1}^{€} - y_{t+1}^{€/\$})}$

Note on the algebra deriving the price of the € ZC bond that is collateralized in $.

Based on the diagram in Panel C, the no-arbitrage brake-even at $t+1$ is:

$$€1 = D_t^{\$} \times e^{o_{t+1}^{\$}} \times F_{t+1}$$

since $D_t^{\$} = D_t^{€/\$}/S_t$ and counterparty risk free FX forward is $F_{t+1} = S_t \times e^{r_{t+1}^{€} - r_{t+1}^{\$}}$, substituting:

$$€1 = D_t^{€/\$}/S_t \times e^{o_{t+1}^{\$}} \times S_t \times e^{r_{t+1}^{€} - r_{t+1}^{\$}}$$

since $y_{t+1} = r_{t+1} - o_{t+1}$, then $r_{t+1} = y_{t+1} + o_{t+1}$, substituting:

$$€1 = D_t^{€/\$} \times e^{o_{t+1}^{\$}} \times e^{y_{t+1}^{€} + o_{t+1}^{€} - y_{t+1}^{\$} - o_{t+1}^{\$}}$$
$$€1 = D_t^{€/\$} \times e^{y_{t+1}^{€} + o_{t+1}^{€} - y_{t+1}^{\$}}$$
$$D_t^{€/\$} = e^{-(y_{t+1}^{€} + o_{t+1}^{€} - y_{t+1}^{\$})}$$

since $y^{€/\$} = y_{t+1}^{€} - y_{t+1}^{\$}$, substituting, the price of the bond is:

$$D_t^{€/\$} = e^{-(o_{t+1}^{€} - y_{t+1}^{€/\$})}$$

Figure 4: Cash Flows of a Collateralized Libor-Based Cross Currency Basis Swap. This diagram illustrates the cash flows generated from collateralized cross currency swap. Under the swap a counterparty is borrowing € and lending \$ synthetically. The counterparty receives the 3-month Libors $L^{\$}(T_{n-1}, T_n)$ accrued every δ fraction of a year (3-months - being quarter of a year or 0.25) on the $S_0^{\$}$ notional and pays the 3-month Libors plus the xccy basis $(L^{€}(T_{n-1}, T_n) + x_n)$ accrued every δ fraction of the year on the €1 notional. The notional face amounts are exchanged both at time 0 and at time T, converted at the spot FX rate, S_0, one unit of € for \$ currency. $h_{\$}$ is the MtM in \$ currency that the counterparty needs to pay if it is negative or that the counterparty needs to receive if it is positive. $o_{t-1}^{\$}$ is the collateral rate set at $t-1$ and paid at t , e.g. the annualized overnight \$ FedFunds (OIS) rate. This rate accrues from $t-1$ to t, representing by the day fraction ϕ of 1/365.

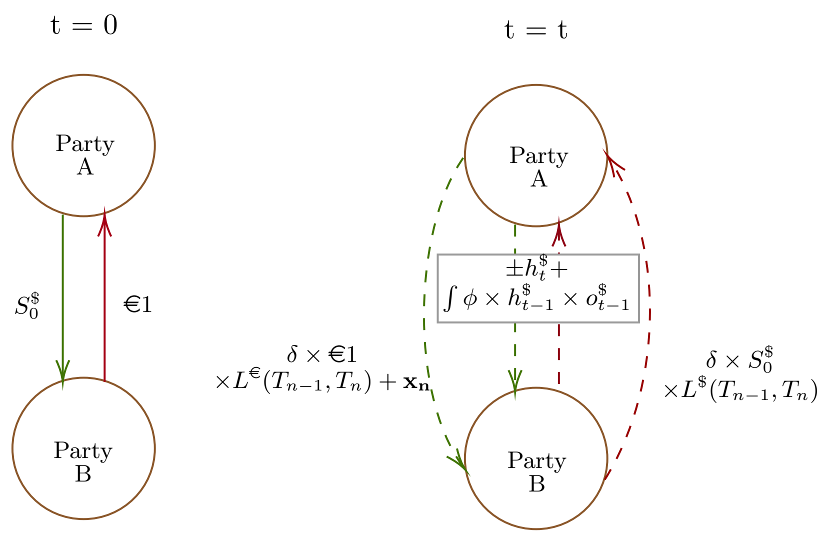
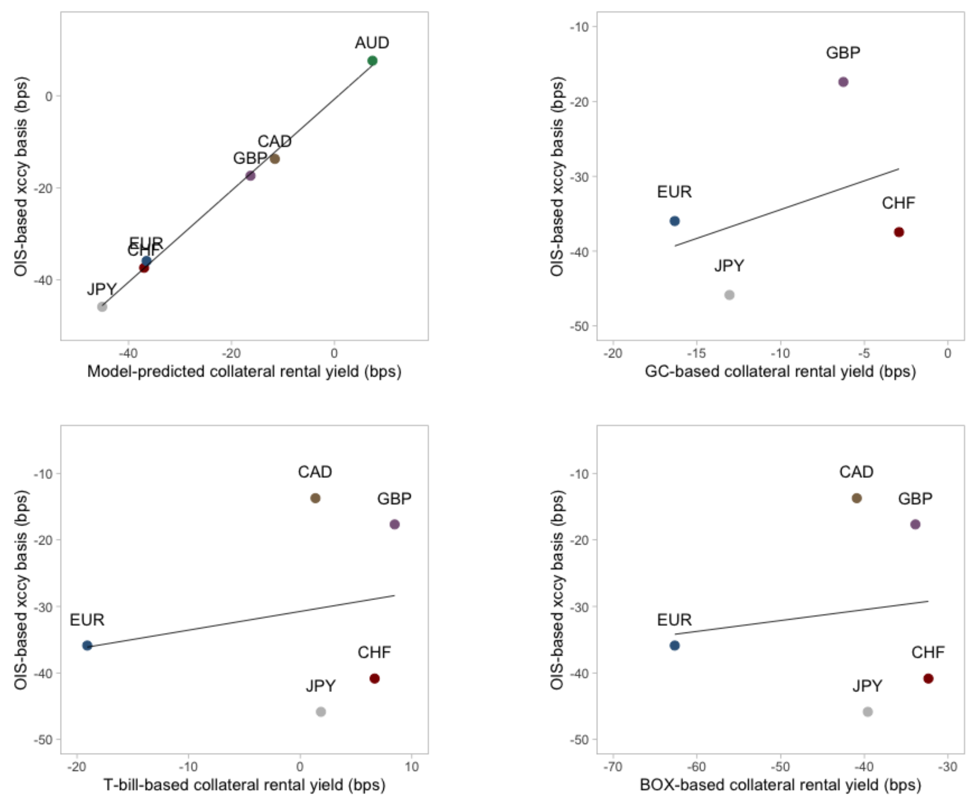


Figure 5: Cross-Section of Currency Basis and Collateral Rental Yield (2009-2020). This figure shows the cross-sectional relationship between the xccy basis on the y-axis and the various collateral rental yield proxies on the x-axis for the short-term (Panel A) and long-term (Panel B) tenor. The 3-month OIS-based xccy basis is calculated as: $o^{\$}_{t,t+1} - (o^{i}_{t,t+1} - \frac{1}{n}(f_{t+1} - s_t))$, where $o^{\$}_{t,t+1}$ and $o^{i}_{t,t+1}$, denote the US and foreign 3-month OIS rates and $(f_{t+1} - s_t)$ denotes the forward premium obtained from the forward and spot exchange rates. The Libor-based xccy basis is obtained from xccy basis swap contracts directly. The GC-based collateral rental yield is the difference in the differenced foreign currency 3-month GC repo and OIS rates and the differential less the US dollar 3-month GC repo and OIS rates; the T-bill-based collateral rental yield is the difference in the differenced foreign currency foreign currency 3-month T-bill and OIS rates less the US dollar 3-month T-Bill and OIS rates; the BOX-based collateral rental yield is the difference in the differenced foreign currency 3-month T-bill and OIS rates less the US dollar 6-month BOX and OIS rates; and the model-predicted collateral rental yield is the affine model generated collateral rental yield for 3-month, 5-year, and 10-year horizon. The countries and currencies are denoted by the abbreviations: Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), euro (EUR), British Pound (GBP), and Japanese yen (JPY).

Panel A: Short-Term OIS-based CIP - 3-month horizon



Panel B: Long-Term Libor-based CIP

5-year horizon **10-year horizon**

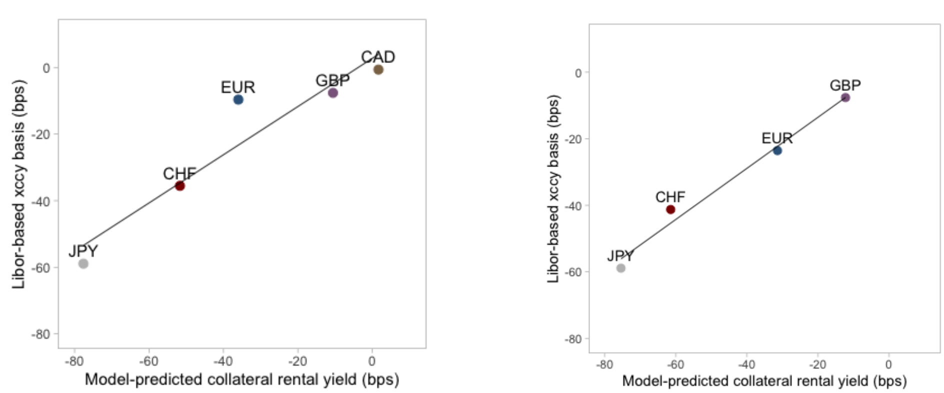
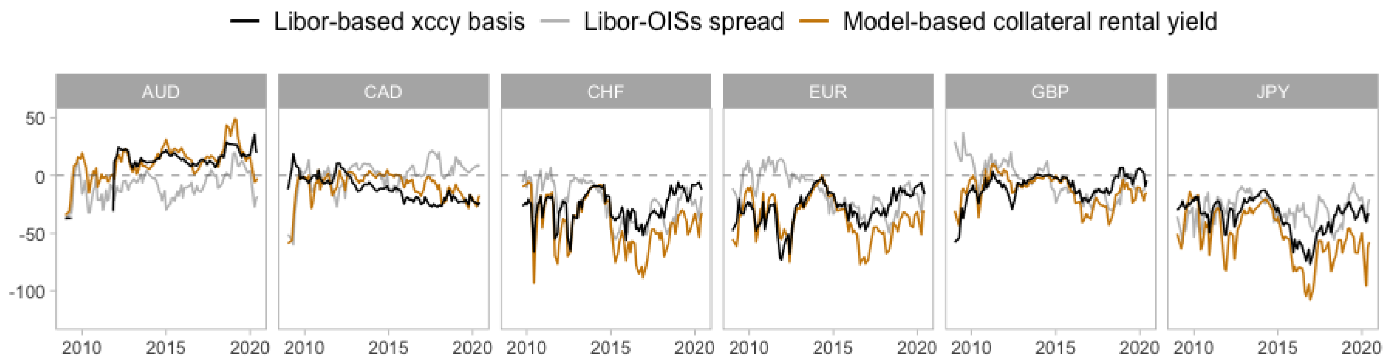
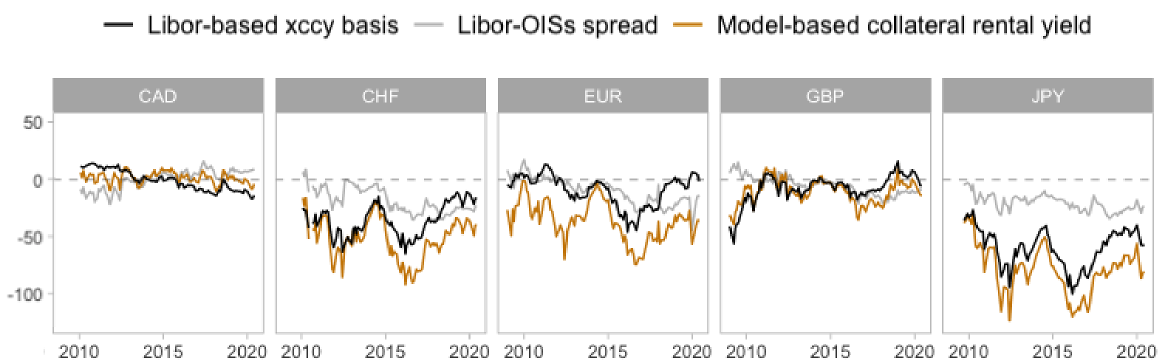


Figure 6: Decomposing the Long-Term Libor-Based Xccy Basis.
This figure shows the contribution to the standard Libor-based xccy bases from the model-predicted collateral rental yield versus the *LiborOISs* spread, which the difference of the spread between the n-tenor Libor and n-tenor OIS zero rates of the foreign currency and the spread between the n-tenor Libor and n-tenor OIS of the US dollar zero rates (in basis points). Panel A, Panel B, and Panel C plot the relationship for n =1-, 5-, and 10-year maturity horizon, respectively. The standard Libor-based xccy basis is obtained from xccy basis swap prices directly. The model-predicted collateral rental yield is the affine model generated collateral rental yield (in basis points). The countries and currencies are denoted by the abbreviations: Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), euro (EUR), British Pound (GBP), and Japanese yen (JPY).

Panel A: 1-year horizon



Panel B: 5-year horizon



Panel C: 10-year horizon

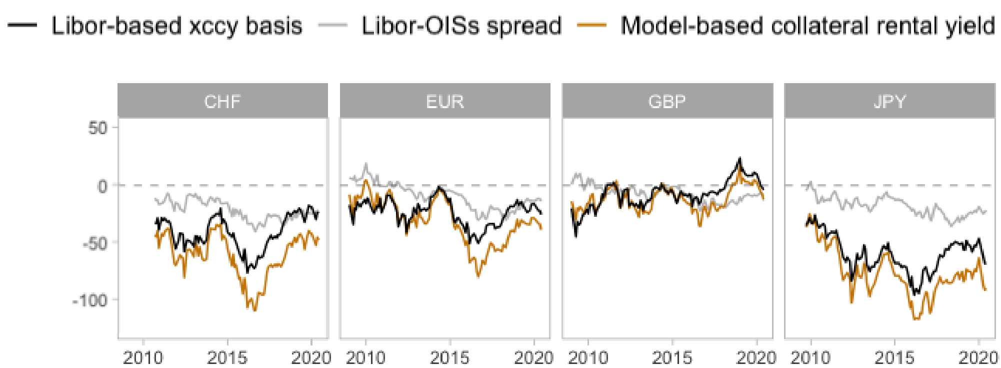
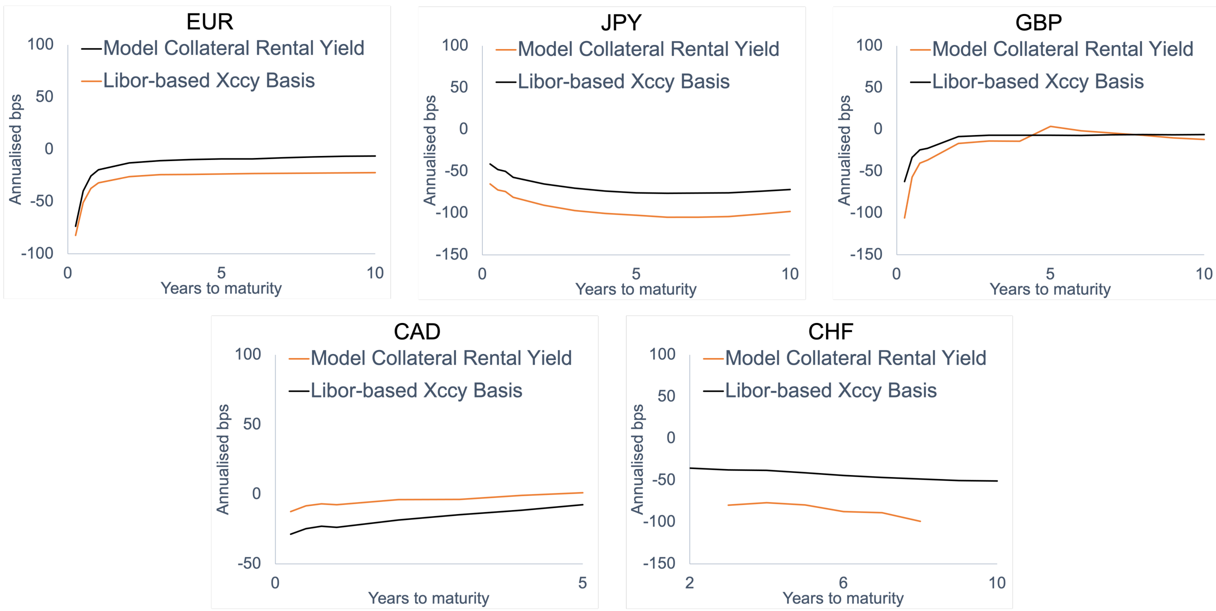


Figure 7: Term Structure of Libor-Based Xccy Basis vs. Model-Predicted Collateral Rental Yield.
The black line represents the Libor-based xccy basis, in the market for each tenor and the brown line represents the model-predicted collateral rental yield, extracted and modeled using the affine model for each tenor. Presented are results for date 03/16/2020 for different currencies against the US dollar (Panel A) and for selected dates for the EUR against the US dollar (Panel B).

Panel A: All Currencies for 3/16/2020



Panel B: EUR currency for selected dates

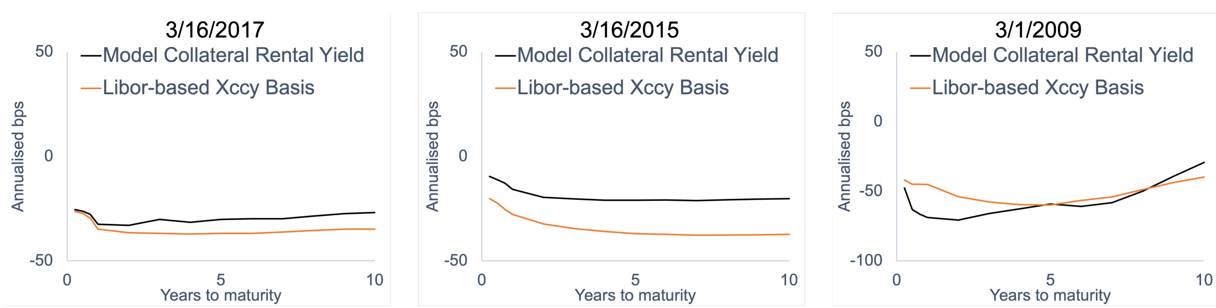
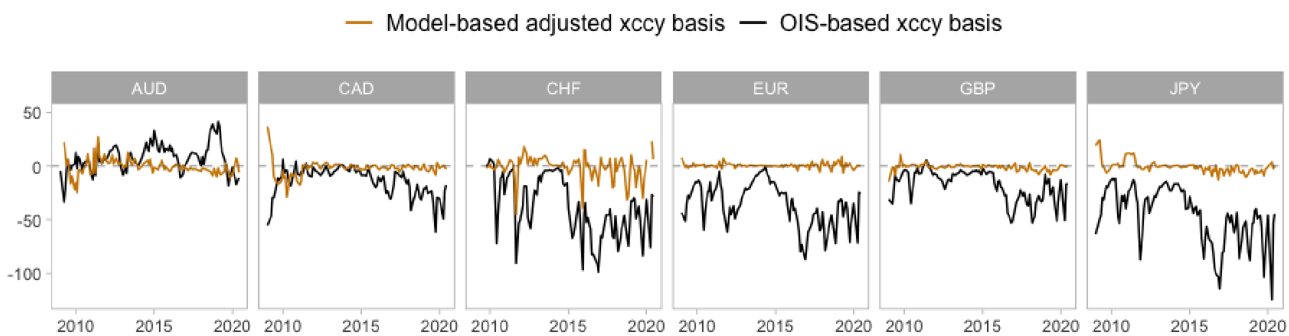
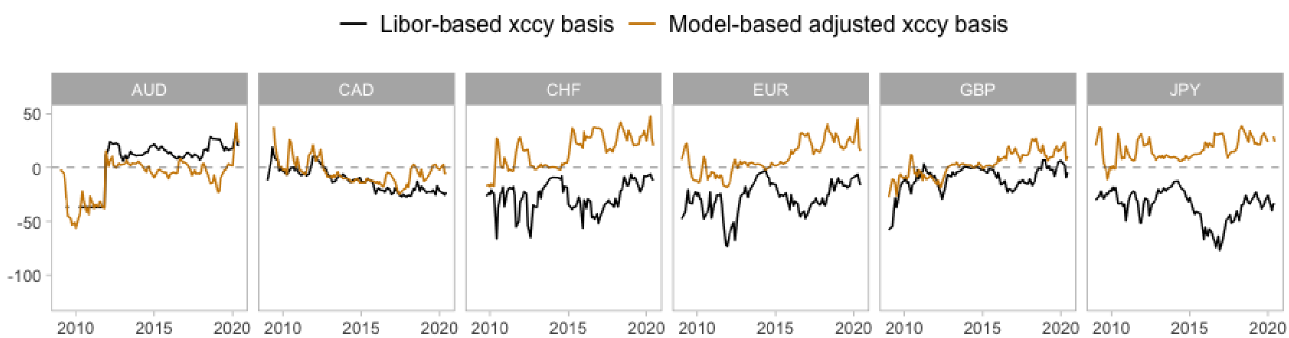


Figure 8: Standard Versus Model-Based Collateral-Adjusted CIP Deviations.
This figure shows the monthly xccy basis versus the model-based collateral adjusted xccy basis for G7 currencies for the full sample 1/1/2009-5/31/2020. The 3-month standard OIS-based basis is calculated as: $o^{\$}_{t,t+1} - (o^{i}_{t,t+1} - \frac{1}{n}(f_{t+1} - s_t))$, where $o^{\$}_{t,t+n}$ and $o^{i}_{t,t+1}$, denote the US and foreign 3-month OIS rates and $(f_{t+1} - s_t)$ denotes the forward premium obtained from the forward and spot exchange rates. The standard Libor-based xccy basis is obtained from xccy basis swap contract prices directly. The model-based adjusted xccy basis stands for the re-calculated xccy basis adjusted for the model-predicted collateral rental yield.

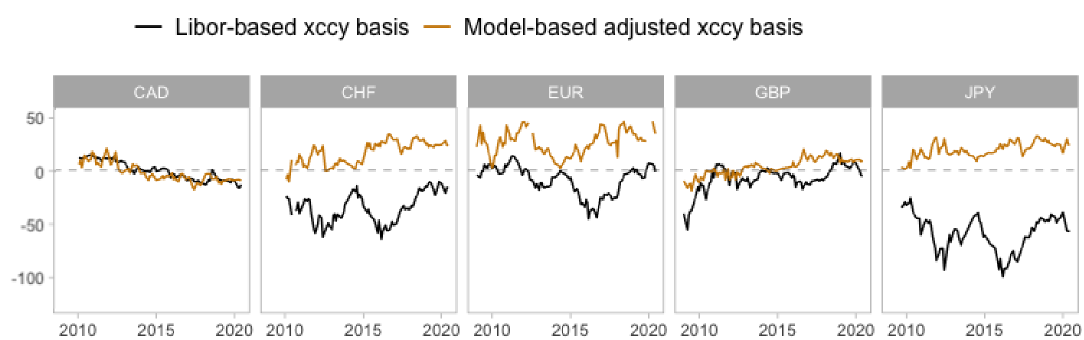
Panel A: 3-month Horizon



Panel B: 1-year Horizon



Panel C: 5-year Horizon



Panel D: 10-year Horizon

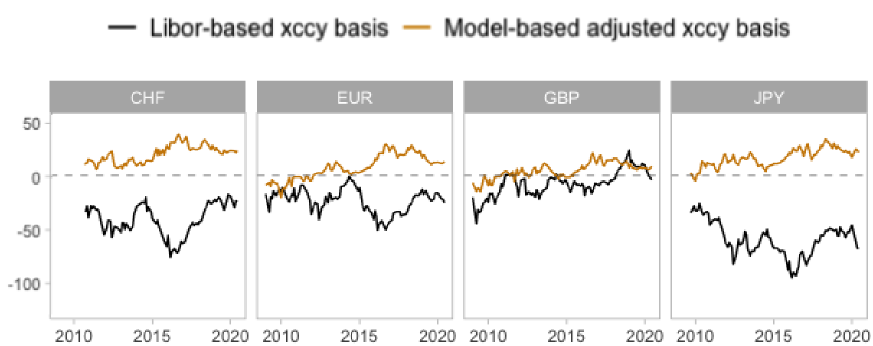


Table 1: Short- and Long-Term Standard OIS-based vs. Collateral-Adjusted CIP Deviations
This table reports the mean of daily short-term OIS-based xccy basis (Panel A) and of monthly long-term OIS-based xccy basis (Panel B) versus their maturity matched collateral-adjusted xccy bases for G7 currencies for two different periods. Similar to Du and Schregner (2021), the two samples are the "Crisis" periods, which include August 2008 - December 2009 (GFC), November 2011 - February 2012, and March 2020 - May 2020 (Covid), and the "Post-Crisis" period that runs from January 1, 2010 to May 31, 2020 and excludes the Crisis period. Standard deviations are shown in the parentheses. The short-term n-month OIS-based basis is calculated as: $o^{\$}_{t,t+n} - (o^{i}_{t,t+n} - \frac{1}{n}(f_{t,n} - s_t))$, where $o^{\$}_{t,t+n}$ and $o^{i}_{t,t+n}$, denote the US and foreign n-month OIS rates and $(f_{t,n} - s_t))$ denotes the forward premium obtained from the forward $f_{t,t+n}$ and spot s_t exchange rates. The long-term OIS-based xccy basis is refer to as synthetic and is calculated using the identities (11), (12), and (13) in the main paper by substituting the coupon cashflows indexed to the Libor curves with coupon cash flows indexed to the extracted market OIS curves. This allows to effectively parse out the Libor-OISs spreads from the xccy Libor-indexed swap price observed directly in the market. The n stands for $1w$ (1-week), $1m$ (1-month), $3m$ (3-month), $1y$ (1-year), $5y$ (5-year), and $10y$ (10-year); $x^{adj}_{n,gc}$ stands for the re-calculated OIS-based xccy basis adjusted for the GC-based collateral rental yield $y^{i/\$}_{n,gc}$, which the is difference in the differenced foreign currency n-month GC repo and OIS rates and the differential less the US dollar n-month GC repo and OIS rates; $x^{adj}_{3m,tbill}$ stands for the re-calculated OIS-based xccy basis adjusted for the T-bill-based collateral rental yield $y^{i/\$}_{3m,tbill}$, which is difference in the differenced foreign currency foreign currency 3-month T-bill and OIS rates less the US dollar 3-month T-Bill and OIS rates; $x^{adj}_{3m,BOX}$ stands for the re-calculated OIS-based xccy basis adjusted for the BOX-based collateral rental yield $y^{i/\$}_{3m,BOX}$, which is difference in the differenced foreign currency 3-month T-bill and OIS rates less the US dollar 6-month BOX and OIS rates: and $x^{adj}_{n,AF}$ stands for the synthetic OIS-based xccy basis re-calculated and adjusted for the affine model-predicted collateral rental yield $y^{i/\$}_{n,AF}$. The countries and currencies are denoted by the abbreviations: Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), euro (EUR), British Pound (GBP), and Japanese yen (JPY).

PANEL A: Short-Term Mean CIP deviations

		1W		1M		3M				
	Currency	x^{OIS}_{1w}	$x^{adj}_{1w,gc}$	x^{OIS}_{1m}	$x^{adj}_{1m,gc}$	x^{OIS}_{3m}	$x^{adj}_{3m,gc}$	$x^{adj}_{3m,tbill}$	$x^{adj}_{3m,BOX}$	$x^{adj}_{3m,AF}$
Post-Crisis	EUR	-26.20	-14.33	-35.66	-21.02	-35.47	-19.64	-10.50	20.15	-4.39
		(62.79)	(61.91)	(29.13)	(25.83)	(21.1)	(17.74)	(15.62)	(14.88)	(2.48)
	JPY	-35.45	-23.28	-43.68	-27.52	-45.21	-26.38	-41.08	-10.88	-6.23
		(59.21)	(55.91)	(34.78)	(28.55)	(24.55)	(17.18)	(20.4)	(16.08)	(4.76)
	CHF	-42.85	-27.35	-53.97	-29.57	-37.37	-28.38	-40.54	-12.53	-6.23
		(90.04)	(88.5)	(41.78)	(38.95)	(27.83)	(23.41)	(25.52)	(24.89)	(11.2)
	GBP	-15.3	-2.83			-16.61	-1.89	-18.8	11.73	-5.99
		(107.81)	(108.25)			(14.12)	(16.11)	(15.32)	(13.77)	(2.33)
	CAD					-11.88		-6.98	23.8	-7.29
						(10.79)		(11.92)	(11.59)	(4.98)
	AUD					10.95				-5.53
						(12.18)				(6.77)
	Mean	-27.05	-14.58	-41.3	-24.87	-33.67	-19.07	-23.53	6.51	-5.94
		(82)	(81.08)	(33.84)	(29)	(24.81)	(21.52)	(23.45)	(22.78)	(6.23)
Crisis	EUR	-54.34	-55.90	-59.80	-50.83	-55.68	-39.28	-38.12	32.76	-4.25
		(99.2)	(97.12)	(80.32)	(66.63)	(61.52)	(45.52)	(55.49)	(40.06)	(2.86)
	JPY	-56.02	-50.70	-71.12	-57.03	-71.18	-53.05	-84.50	-13.64	-1.21
		(84.62)	(86.35)	(94.97)	(83.39)	(75.81)	(63.03)	(96.71)	(50.46)	(10.49)
	CHF	-62.84	-46.2	-71.39	-51.16	-24.97	-25.51	-39.07	-13.57	13.21
		(80.28)	(73.83)	(67)	(53.36)	(39.78)	(25.58)	(33.17)	(9.19)	(24.99)
	GBP	-30.28	-60.28			-38.54	-56.17	-61.12	8.25	-6.67
		(64.26)	(83.31)			(54.4)	(73.38)	(77.28)	(35)	(6.38)
	CAD					-50.54		-51.45	17.94	-5.75
						(53.7)		(56.05)	(23.62)	(17.18)
	AUD					-33.48				2.07
						(64.3)				(25.4)
	Mean	-47.66	-55.16	-65.92	-53.74	-52.11	-47.13	-57.27	10.11	-1.95
		(84.47)	(88.42)	(86.73)	(74.12)	(64.35)	(59.94)	(73.06)	(41.38)	(15.82)

PANEL B: Long-Term Mean CIP deviations

	Currency	1Y x_{1y}^{OIS}	1Y x_{1y}^{adj}	5Y x_{5y}^{OIS}	5Y x_{5y}^{adj}	10Y x_{10y}^{OIS}	10Y x_{10y}^{adj}
Post-Crisis	EUR	-28.28	-1.17	-10.80	11.27	-23.99	-5.75
		(14.89)	(14.39)	(14.03)	(12.48)	(11.67)	(11.12)
	JPY	-36.2	7.61	-59.66	4.4	-59.68	2.04
		(15.45)	(9.71)	(16.87)	(6.71)	(15.71)	(7.95)
	CHF	-27.17	5.63	-35.76	1.18	-41.63	5.15
		(13.62)	(15.21)	(14.13)	(10.71)	(14.87)	(8.38)
	GBP	-7.76	-5.64	-5.12	-10.8	-5.79	-9.23
		(7.88)	(10.37)	(7.92)	(7.12)	(10.25)	(6.57)
	CAD	-13.02	-15.75	-0.27	-17.15		
		(9.72)	(9.97)	(8.65)	(8.57)		
	AUD	4.96	-18.82				
		(21.91)	(16.72)				
	Mean	-17.91	-4.69	-22.31	-2.2	-32.62	-2.07
		(20.21)	(16.35)	(25.74)	(13.94)	(24.16)	(10.38)
Crisis	EUR	-27.24	-0.13	1.38	13.48	-19.83	-19.13
		(12.71)	(18.36)	(4.61)	(12.13)	(5.92)	(8.91)
	JPY	-27.39	8.87	-42.32	-3.05	-45.09	-5.11
		(5.71)	(21.32)	(13.31)	(13.53)	(18.1)	(13.33)
	CHF	-16.41	0.77	-18.5	10.56	-26.4	7.28
		(10.27)	(32.4)	(3.5)	(3.03)	(4.06)	(1.18)
	GBP	-28.12	-18.36	-29.18	-22.74	-23.86	-20.83
		(19.6)	(15.05)	(17.43)	(9.76)	(14.01)	(8.02)
	CAD	-0.94	13.51	-16.58	-23.81		
		(15.26)	(26.33)	(0.0016)	(0.13)		
	AUD	-23.78	-28.61				
		(27.8)	(33.41)				
	Mean	-21.12	-4.52	-19.30	-4.64	-26.49	-15.21
		(19.46)	(28.04)	(20.32)	(19.54)	(14.74)	(12.4)

Table 2: Panel Regression Results for the Short-Term OIS-based Xccy Basis on the Observable Proxies for the Collateral Rental Yield

This table shows panel regression results for the daily level/monthly changes (Panel A/Panel B) in the OIS-based xccy basis (dependent variable), x_n^{OIS}, on level/monthly changes (Panel A/Panel B) in the maturity matched, n, collateral rental yield proxy, $y_n^{i/\$}$, and other controls in the period between 1 January 2009 and 31 May 2020, where $n = 1w$ (1-week), $1m$ (1-month), and $3m$ (3-month). The n-month OIS-based basis is calculated as: $o^{\$}_{t,t+n} - (o^{i}_{t,t+n} - \frac{1}{n}(f_{t,n} - s_t))$, where $o^{\$}_{t,t+n}$ and $o^{i}_{t,t+n}$, denote the US and foreign n-month OIS rates and $(f_{t,n} - s_t))$ denotes the forward premium obtained from the log of the forward $f_{t,t+n}$ and spot s_t exchange rates. The independent variables are: $y^{i/\$}_{n,GC}$, spread between the differential between foreign currency n-month GC repo and OIS rates and the differential between the US dollar n-month GC repo and OIS rates (in basis points); $y^{i/\$}_{Tbill}$, spread between the differential between foreign currency 3-month T-bill and OIS rates and the differential between the US dollar 3-month T-bill rates and OIS rates (in basis points); $y^{i/\$}_{BOX}$, spread between the differential between foreign currency 3-month T-bill and OIS rates and the differential between the US dollar 6-month BOX implied rates and OIS rates (in basis points); $Qend$ is an indicator variable that equals 1 for the last 6 days of the quarter and equals 0 if otherwise ; $Yend$ is an indicator variable that equals 1 for the last month of the year and equals 0 if otherwise; $LiborOISs$, the difference of the spread between the 3-month Libor and 3-month OIS of the foreign currency and the spread between the 3-month Libor and 3-month OIS of the US dollar (in basis points); $FXbidask$, the ask normalized spread between the bid and ask of the bilateral n-month FX forward exchange rate (in pips); $US\ factor$ is the trade weighted US dollar index created by the FED; $\Delta lnFX$, the change in the log FX bilateral spot exchange rate of the US dollar against the foreign currency; $lnVol$, the log of implied volatility on effective 3-month at-the-money FX options; $lnVix$, the log of the VIX index. The currencies included are: Canadian dollar (CAD), Swiss franc (CHF), euro (EUR), British Pound (GBP), and Japanese yen (JPY) of Currency and year fixed effects are included in all specifications. Robust, two-way clustered standard errors by currency and time are shown in the parenthesis for specifications in changes. HAC-adjusted SE at 90 lags for daily specification in levels. Data source: BNP Paribas, Bloomberg, Tullet Prebon, Swiss Stock Exchange, Bank of England. Significance: *** p<0.01, ** p<0.05, * p<0.1.

PANEL A: *In Levels*

	Dependent variable: x_n^{OIS}									
	$n = 1w$		$n = 1m$		$n = 3m$					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$y^{i/\$}_{n,GC}$	1.10***	0.91**	1.42***	1.23***	0.51***	0.18***				
	(0.38)	(0.36)	(0.32)	(0.22)	(0.11)	(0.07)				
$y^{i/\$}_{3m,Tbill}$							0.56***	0.50***		
							(0.06)	(0.05)		
$y^{i/\$}_{3m,BOX}$									0.60***	0.43***
									(0.04)	(0.05)
$Qend$		−25.78***		-8.24**		1.90		0.61		0.58
		(7.19)		(3.74)		(1.41)		(1.21)		(0.97)
$Yend$		−36.11**		−43.07***		−2.62**		−3.25**		−3.80**
		(14.73)		(9.66)		(1.07)		(1.37)		(1.59)
$LiborOISs$		0.33*		0.68***		0.63***		0.22***		0.25***
		(0.18)		(0.14)		(0.07)		(0.02)		(0.03)
$FXbidask$		−43.99*		16.68		−11.90**		−18.80***		−22.06***
		(22.85)		(10.60)		(5.89)		(4.54)		(6.49)
$US\ factor$		0.10		0.32		−1.04***		−1.30***		−0.82***
		(0.79)		(0.60)		(0.25)		(0.28)		(0.24)
$\Delta lnFX$		150.13		30.05		57.80*		41.54		26.03
		(124.38)		(56.69)		(31.46)		(25.67)		(24.60)
$lnVol$		23.02**		8.11		−0.92		−2.79		−0.90
		(9.51)		(8.96)		(2.42)		(2.58)		(3.35)
$lnVix$		−5.40		2.22		−6.42*		−8.80**		−3.39
		(8.64)		(7.02)		(3.70)		(4.14)		(4.04)
Currency pairs	4	4	3	3	4	4	5	5	5	5
Within Adj-R^2	0.02	0.08	0.37	0.46	0.09	0.33	0.15	0.38	0.39	0.51
Observations	8,440	7,576	5,458	4,854	10,491	9,520	14,604	13,355	11,234	11,127

PANEL B: *In Changes*

	Dependent variable: Δx_n^{OIS}									
	$n = 1w$		$n = 1m$		$n = 3m$					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$\Delta y_{n,GC}^{i/\$}$	0.52***	1.12***	0.81**	0.54**	0.34**	0.12**				
	(0.12)	(0.16)	(0.36)	(0.22)	(0.13)	(0.04)				
$\Delta y_{3m,Tbill}^{i/\$}$							0.39***	0.37***		
							(0.08)	(0.08)		
$\Delta y_{3m,BOX}^{i/\$}$									0.31***	0.20***
									(0.06)	(0.06)
$Yend$		−40.32***		−51.29***		−2.45***		−2.87**		−3.80**
		(9.57)		(12.68)		(1.27)		(1.34)		(1.60)
$\Delta LiborOISs$		0.15		−0.52		0.43***		0.28***		0.20**
		(0.19)		(0.41)		(0.11)		(0.07)		(0.08)
$\Delta FXbidask$		25.72		−107.44*		−7.69		0.29		0.73
		(20.45)		(59.64)		(11.21)		(9.16)		(10.98)
$\Delta US\ factor$		−2.11**		−3.43		−1.85***		−1.56***		−0.96*
		(1.03)		(2.34)		(0.67)		(0.49)		(0.51)
$\Delta lnFX$		30.27		45.01		34.03		24.92		48.72*
		(54.06)		(138.34)		(32.26)		(24.53)		(24.92)
$\Delta lnVol$		30.35***		7.55		−4.49		−1.67		4.66
		(11.52)		(31.26)		(7.08)		(5.20)		(5.60)
$\Delta lnVix$		−6.94		−34.15*		−9.40**		−9.11***		−8.70**
		(7.41)		(17.63)		(4.74)		(3.34)		(3.72)
Currency pairs	4	4	3	3	4	4	5	5	5	5
Within Adj-R^2	0.01	0.25	0.01	0.22	0.01	0.18	0.02	0.26	0.05	0.19
Observations	272	206	175	130	340	262	444	356	296	296

Table 3: Difference-in-Difference of the Short-Term Collateral Rental Yield Pre and Post-Crisis
This table reports the results from a difference-in-difference panel regression of daily short-term OIS-based xccy basis on its maturity matched collateral rental yield proxy and a dummy denoted "Post-Crisis" indicating 1 for the period from January 1, 2010 to May 31, 2020 excluding the Crisis periods which are the GFC from August 2008 - December 2009, and the Covid from March 2020 - May 2020 and 0 otherwise (subsamples are similar to Du and Schregner (2021)). The short-term n-month OIS-based xccy basis is calculated as: $o^{\$}_{t,t+n} - (o^{i}_{t,t+n} - \frac{1}{n}(f_{t,n} - s_t))$, where $o^{\$}_{t,t+n}$ and $o^{i}_{t,t+n}$, denote the US and foreign n-month OIS rates and $(f_{t,n} - s_t))$ denotes the forward premium obtained from the forward $f_{t,t+n}$ and spot s_t exchange rates. The n stands for $1w$ (1-week), $1m$ (1-month), and $3m$ (3-month). The collateral rental yield proxies are: $y^{i/\$}_{n,gc}$, the difference in the differenced foreign currency n-month GC repo and OIS rates and the differential less the US dollar n-month GC repo and OIS rates; $y^{i/\$}_{tbill}$, the difference in the differenced foreign currency foreign currency 3-month T-bill and OIS rates less the US dollar 3-month T-Bill and OIS rates; and $y^{i/\$}_{BOX}$, the difference in the differenced foreign currency 3-month T-bill and OIS rates less the US dollar 6-month BOX and OIS rates. The countries and currencies used are: Canadian dollar (CAD), Swiss franc (CHF), euro (EUR), British Pound (GBP), and Japanese yen (JPY). Currency and year fixed effects are included in all specifications. HAC-adjusted SE at 90 lags. Data source: BNP Paribas, Bloomberg, Tullet Prebon, Swiss Stock Exchange, Bank of England. Significance: *** p<0.01, ** p<0.05, * p<0.1.

	Dependent variable: x^{OIS}_n				
	$n = 1w$	$n = 1m$	$n = 3m$		
	(1)	(2)	(3)	(4)	(5)
$y^{i/\$}_{n,gc}$	0.12	0.53	0.39		
	(0.25)	(0.48)	(0.30)		
$y^{i/\$}_{n,gc} \times PostCrisis$	0.93**	1.14**	0.49**		
	(0.38)	(0.45)	(0.20)		
$y^{i/\$}_{tbill}$				−0.23	
				(0.21)	
$y^{i/\$}_{tbill} \times PostCrisis$				0.91***	
				(0.20)	
$y^{i/\$}_{BOX}$					0.86***
					(0.07)
$y^{i/\$}_{BOX} \times PostCrisis$					0.16**
					(0.08)
$PostCrisis$	28.08*	21.06*	28.75***	22.50**	−3.82
	(15.12)	(11.39)	(4.52)	(11.21)	(3.04)
Currency pairs	4	3	4	5	5
Within Adj-R^2	0.03	0.30	0.21	0.16	0.52
Observations	8616	5546	10667	14954	11565

Table 4: Panel Regression Results for the Long-Term Synthetic OIS-Based Xccy Basis on the Unobservable Affine Model Generated Collateral Rental Yield

This table shows panel regression results for the monthly level/changes (Panel A/Panel B) in the synthetic OIS-based xccy basis (dependent variable), x_n^{OIS}, on level/changes (Panel A/Panel B) in the maturity matched, n, affine model-predicted collateral rental yield $y_{n,AF}^{i/\$}$ (in basis points), and other controls in the period between 1 January 2009 and 31 May 2020, where $n = 3m$ (3-month), $1y$ (1-year), $5y$ (5-year), and $10y$ (10-year). The other independent variables are factors related to regulation, which are $Yend$ is an indicator variable that equals 1 for the last month of the year and equals 0 if otherwise, the factors for leverage of security broker dealers form Adrian, Etula, and Muir (2014) (AEM) and for leverage and capital of bank holding companies of He, Kelly, and Manela (2017) (HKM); $LiborOISs$, the difference of the spread between the 3-month Libor and 3-month OIS of the foreign currency and the spread between the 3-month Libor and 3-month OIS of the US dollar (in basis points); $FXbidask$, the ask normalized spread between the bid and ask of the bilateral 3-month FX forward exchange rate (in pips); $US\ factor$ is the trade weighted US dollar index created by the FED; $\Delta lnFX$, the change in the log FX bilateral spot exchange rate of the US dollar against the foreign currency; $lnVol$, the log of implied volatility on effective 3-month at-the-money FX options; $lnVix$, the log of the VIX index. The currencies used are: Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), euro (EUR), British Pound (GBP), and Japanese yen (JPY). Currency and year fixed effects are included in all specifications. Robust, two-way clustered standard errors by currency and time are shown in the parenthesis for the specifications in changes. HAC-adjusted SE at 5 lags for specification in levels. Significance: *** p<0.01, ** p<0.05, * p<0.1.

PANEL A: *In Levels*

	Dependent variable: x_n^{OIS}							
	$n = 3m$		$n = 1y$		$n = 5y$		$n = 10y$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$y_{n,AF}^{i/\$}$	0.87***	0.91***	0.56***	0.59***	0.65***	0.66***	0.78***	0.81***
	(0.02)	(0.03)	(0.03)	(0.05)	(0.03)	(0.04)	(0.02)	(0.02)
$Yend$		−3.55		−2.09		−0.43		1.02
		(4.03)		(1.93)		(1.39)		(0.75)
$HKM\ leverage$		0.01		0.01		−0.003		−0.01
		(0.04)		(0.02)		(0.01)		(0.03)
$HKM\ capital$		−15.27*		13.95		−9.39		−12.97
		(10.83)		(10.20)		(7.49)		(15.01)
$LiborOISs$		0.01		0.02		−0.06**		−0.16***
		(0.01)		(0.03)		(0.03)		(0.02)
$US\ factor$		−0.20		0.46		0.04		−0.04
		(0.14)		(0.29)		(0.18)		(0.10)
$\Delta lnFX$		−0.21		−5.11		−19.68		3.90
		(9.78)		(17.25)		(12.83)		(6.81)
$lnVol$		−1.53		−5.19		5.00*		−1.25
		(2.11)		(3.74)		(2.56)		(1.32)
$FXbidask$		−3.86		36.60***		26.94***		−1.16
		(6.67)		(11.79)		(8.37)		(4.28)
$lnVix$		−0.54		1.40		−0.25		1.91
		(2.03)		(3.59)		(2.44)		(1.33)
Currency pairs	6	6	6	6	5	5	4	4
Within Adj-R^2	0.80	0.84	0.35	0.38	0.53	0.56	0.85	0.87
Observations	582	457	582	457	466	366	373	292

PANEL B: *In Changes*

	Dependent variable: Δx_n^{OIS}							
	$n = 3m$		$n = 1y$		$n = 5y$		$n = 10y$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\Delta y_{n,AF}^{i/\$}$	0.87***	0.89***	0.47***	0.65***	0.47***	0.48***	0.67***	0.60***
	(0.02)	(0.04)	(0.02)	(0.03)	(0.02)	(0.03)	(0.02)	(0.03)
$Yend$		−2.44		3.22		−1.79		−2.14
		(3.31)		(4.89)		(2.71)		(2.64)
$HKM\ leverage$		−0.003		0.01		−0.01		−0.005
		(0.004)		(0.03)		(0.02)		(0.02)
$HKM\ capital$		5.47		0.58		0.23		2.05
		(7.40)		(4.98)		(4.04)		(3.56)
$\Delta LiborOISs$		−0.13		−0.28		−0.05**		−0.11***
		(0.20)		(0.42)		(0.02)		(0.02)
$\Delta US\ factor$		−0.20		−0.36		−0.20		−0.18
		(0.29)		(0.26)		(0.16)		(0.14)
$\Delta lnFX$		−14.72		−8.80		−6.67		0.74
		(14.08)		(9.43)		(7.69)		(6.58)
$\Delta lnVol$		−2.93		−0.88		2.37		−0.27
		(3.14)		(2.10)		(1.71)		(1.51)
$\Delta FXbidask$		4.32		−2.73		0.88		−2.73
		(5.28)		(3.54)		(2.90)		(2.36)
$\Delta lnVix$		−1.59		4.36***		0.22		0.23
		(2.00)		(1.34)		(1.04)		(0.94)
Currency pairs	6	6	6	6	5	5	4	4
Within Adj-R^2	0.69	0.67	0.44	0.64	0. 56	0.61	0.74	0. 76
Observations	576	409	576	409	460	327	369	261

Table 5: Panel Regression Results for the Various Collateral Rental Yield Measures on Several Factors

This table shows regression results for the monthly level/changes (Panel A/Panel B) in the various measures of the collateral rental yield (dependent variable), $y_n^{i/\$}$, on the level/changes (Panel A/Panel B) of global and counterparty risk proxies and bank balance sheet constraint variables (independent variables) in the period between 1 January 2009 and 31 May 2020 for up to 6 currency pairs: Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), euro (EUR), British Pound (GBP), and Japanese yen (JPY). The dependent variables are: $y_{3m,GC}^{i/\$}$, the monthly level/change of the spread between the differential between foreign currency 3-month GC repo and OIS rates and the differential between the US dollar 3-month GC repo and OIS rates; $y_{Tbill}^{i/\$}$, the monthly level/change of the spread between the differential between foreign currency 3-month T-bill and OIS rates and the differential between the US dollar 3-month T-bill rates and OIS rates; $y_{BOX}^{i/\$}$, the monthly level/change of the spread between the differential between foreign currency 3-month T-bill and OIS rates and the differential between the US dollar 6-month BOX implied rates and OIS rates; $y_{n,AF}^{i/\$}$, the monthly level/change in the n-tenor affine model-predicted collateral rental yield where $n = 3m$ (3-month), $1y$ (1-year), $5y$ (5-year), and $10y$ (10-year). The independent variables are: factors relating to regulation, which are $Yend$, an indicator variable that equals 1 if the month is the last month of the year and equals 0 if otherwise, the factors for leverage of security broker dealers form Adrian, Etula, and Muir (2014) (AEM) and for leverage and capital of bank holding companies of He, Kelly, and Manela (2017) (HKM); $LiborOISs$, the difference of the spread between the 3-month Libor and 3-month OIS of the foreign currency and the spread between the 3-month Libor and 3-month OIS of the US dollar (in basis points); $FXbidask$, the ask normalized spread between the bid and ask of the bilateral 3-month FX forward exchange rate (in pips); $US\ factor$ is the trade weighted US dollar index created by the FED; $\Delta lnFX$, the change in the log FX bilateral spot exchange rate of the US dollar against the foreign currency; $lnVol$, the log of implied volatility on effective 3-month at-the-money FX options; $lnVix$, the log of the VIX index; Currency and year fixed effects are included in all specifications. HAC-adjusted SE are at 5 lags for monthly specification in levels. Robust, two-way clustered standard errors by currency and time are for the specifications in changes. Significance: *** p<0.01, ** p<0.05, * p<0.1

PANEL A: *In Levels*

	3M				1Y	5Y	10Y
	$y_{3m,GC}^{i/\$}$	$y_{Tbill}^{i/\$}$	$y_{BOX}^{i/\$}$	$y_{3m,AF}^{i/\$}$	$y_{1y,AF}^{i/\$}$	$y_{5y,AF}^{i/\$}$	$y_{10y,AF}^{i/\$}$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$Yend$	−6.44***	−1.87	−3.08	−6.33***	−5.83***	−5.44***	−5.26**
	(1.96)	(2.01)	(2.37)	(2.04)	(1.90)	(1.99)	(2.27)
$HKM\ leverage$	−0.01	0.01	−0.04***	−0.03***	−0.04***	−0.05***	−0.03***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
$HKM\ capital$	1.23	3.15	−31.96**	−42.36***	−27.80***	−26.40**	−20.81*
	(10.78)	(10.78)	(12.62)	(10.79)	(10.08)	(10.87)	(12.36)
$LiborOISs$	0.11	0.13***	0.28***	0.33***	0.32***	0.34***	0.34***
	(0.23)	(0.04)	(0.04)	(0.02)	(0.02)	(0.03)	(0.06)
$US\ factor$	0.22	0.30	−0.39**	−0.36***	−0.13***	−0.14***	−0.07***
	(0.25)	(0.26)	(0.16)	(0.05)	(0.03)	(0.04)	(0.01)
$\Delta lnFX$	−7.55	−15.11**	−12.92*	−5.89	−7.93	17.57***	33.41***
	(5.96)	(5.99)	(6.95)	(6.09)	(5.69)	(5.79)	(6.48)
$lnVol$	11.58***	−4.41	−14.40***	0.34	−9.43**	−10.52***	0.21
	(3.53)	(3.82)	(4.55)	(3.96)	(3.70)	(3.67)	(4.09)
$FXbidask$	−22.97**	−28.76**	−30.40*	−4.81	−2.96	2.77	27.92**
	(10.98)	(12.73)	(16.77)	(12.58)	(11.75)	(12.22)	(13.10)
$lnVix$	−8.91**	0.65	−0.93	−14.85***	−13.32***	−7.53**	−8.87**
	(3.51)	(3.72)	(4.97)	(3.75)	(3.50)	(3.54)	(4.09)
Currency pairs:	4	5	5	6	6	5	4
Within Adj-R^2	0.16	0.02	0.26	0.44	0.48	0.36	0.17
Observations	264	369	344	457	457	366	292

PANEL B: *In Changes*

	3M				1Y	5Y	10Y
	$\Delta y^{i/\$}_{3m,GC}$	$\Delta y^{i/\$}_{Tbill}$	$\Delta y^{i/\$}_{BOX}$	$\Delta y^{i/\$}_{3m,AF}$	$\Delta y^{i/\$}_{1y,AF}$	$\Delta y^{i/\$}_{5y,AF}$	$\Delta y^{i/\$}_{10y,AF}$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$Yend$	-6.12^{***}	-2.88^{*}	-1.18	-4.63^{***}	-6.44^{***}	-5.63^{***}	-4.96^{***}
	(2.43)	(1.61)	(2.34)	(1.85)	(1.63)	(1.51)	(1.60)
$HKM\ leverage$	-0.001	0.01	0.01	-0.01	-0.01	-0.02^{***}	-0.02^{***}
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
$HKM\ capital$	18.82	0.44	5.34	24.20^{**}	31.12^{***}	3.49	1.37
	(13.72)	(9.12)	(13.16)	(10.36)	(9.15)	(8.56)	(8.96)
$\Delta LiborOISs$	0.07	0.05	0.54^{***}	0.42^{***}	0.37^{***}	0.17^{***}	0.18^{***}
	(0.09)	(0.05)	(0.08)	(0.05)	(0.05)	(0.05)	(0.05)
$\Delta US\ factor$	0.11	0.22	-0.17^{**}	-0.73^{*}	-0.76^{**}	-1.26^{***}	-0.76^{**}
	(0.18)	(0.76)	(0.08)	(0.41)	(0.37)	(0.33)	(0.35)
$\Delta lnFX$	18.53	20.07	42.71^{*}	53.06^{***}	53.21^{***}	3.81	-1.66
	(24.26)	(17.58)	(25.10)	(19.69)	(17.38)	(16.30)	(16.57)
$\Delta lnVol$	2.47	1.97	-18.69^{***}	3.94	-4.40	-16.91^{***}	-12.25^{***}
	(5.64)	(3.88)	(5.58)	(4.42)	(3.90)	(3.50)	(3.71)
$\Delta FXbidask$	-13.77	-13.77^{**}	-26.00^{**}	-15.08^{**}	-16.02^{**}	-14.70^{**}	-0.81
	(8.70)	(6.72)	(11.16)	(7.41)	(6.55)	(6.08)	(5.95)
$\Delta lnVix$	-8.49^{**}	-3.43	0.38	-8.14^{***}	-8.34^{***}	-1.85	-2.28
	(3.61)	(2.44)	(3.89)	(2.79)	(2.46)	(2.20)	(2.36)
Currency pairs:	4	5	5	6	6	5	4
Within Adj-R^2	0.01	0.01	0.16	0.25	0.35	0.33	0.21
Observations	234	321	296	409	409	327	261