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by

Ljubica Georgievska

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ABSTRACT OF THE DISSERTATION

Essays on Cross-Currency Arbitrage and Premia

by

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Doctor of Philosophy in Management

University of California, Los Angeles, 2022

Professor Francis A. Longstaff, Co-Chair

Professor Tyler Stewart Muir, Co-Chair

In Chapter I of this dissertation, I show that a no-arbitrage consistent but costly collateral rental yield explains about two-thirds of the apparent standard Covered Interest Rate (CIP) violations. I proxy this yield with the difference between the risk-free and overnight index swap rates between the cross bilateral currencies and apply it to both short and long-term CIP violations. Further, the results suggest an important direct collateral channel through which costly collateralization explains CIP violations, independent of previously documented global risks and intermediary frictions. In Chapter II, I study the relationship between currency crashes and sovereign defaults. Measuring their relationship is notoriously difficult because these are rare disasters. I take a novel approach. Because they reflect the market's assessment of tail risks, I learn about the risk-neutral distribution of rare currency crashes from prices of far out-of-the-money (FOM) foreign exchange (FX) options and about rare sovereign defaults from prices of credit default swaps (CDS). I find that FOM puts can insure against sovereign credit risk, implying a strong link between currency crashes and sovereign defaults. However, I also find puzzling evidence suggestive of market seg-

mentation, which generates a generous Sharpe ratio in excess of 7.2 when trading between the two markets which disappears during times of crisis. The trade profitability is related to why the same sovereign pays a lower credit interest rate on otherwise equal debt in local currency (LC) versus foreign currency (FC), which is known as the "quanto spread," while the quanto spread, in turn, is related to a developed currency crash distress measure.

The dissertation of Ljubica Georgievska is approved.

Stavros Panageas

Valentin P. Haddad

Francis A. Longstaff, Committee Co-Chair

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University of California, Los Angeles

2022

DEDICATIONS

I would like to dedicate my dissertation to my lovely sister Angelina, brother-in-law Amitav and friends who have always supported me selflessly in all my endeavors and are my lifeline; to my dear parents, who have been compassionate cheerleaders; and to my most wonderful nieces Ava and Aria, who have never failed to make my PhD experience exciting and fun.

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CHAPTER I: Collateral-adjusted CIP Arbitrages

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 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. When calculating CIP violations, this yield should simply be deducted from the xccy basis.

Third, the results not only suggest that the apparent CIP violations reflect costly collateralization in the FX derivative contracts, but also point to an important direct collateral channel through which this costly collateralization contributes to the apparent CIP violations, which is independent of global risk factors and intermediary frictions documented in the literature thus far. However, the evidence also suggests that collateral is not frictionless because it is affected separately by intermediary frictions such as those imposed by quarter- and year-end, capital, and leverage regulations. In this study's no-arbitrage framework, frictionless collateral is rationalized because demand or supply for safe collateral assets, as well as frictions, could affect the proxies and modeling of the risk-free rate that comprises the collateral rental yield. Furthermore, the collateral's opportunity cost may deter intermediaries with high regulatory constraints and targets from expanding their balance sheets with currency derivatives.

Otherwise, according to the framework, it is also hypothetically possible for the collateral to be frictionless; however, this occurs only if such intermediary 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. The results, however, indicate that this is not the case and that the collateral is not completely frictionless. Furthermore, the results indicate that some residual counterparty credit and funding risks are priced into the aggregate FX 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 because, while the currency derivatives market is largely collateralized, it is not entirely 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. 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.

In this paper, I introduce a collateral rental yield as an empirical measure of collateralization costs. 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, I design 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–the collateral rental yield explains a significantly large portion (about two-thirds on average) of the apparent standard CIP violations across maturity horizons. This is because my key purpose is to account for the sizable spread between the risk-free rate and collateral rate. 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

[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).

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 direct collateral channel through which collateral contributes to explaining apparent CIP violations that is independent of some previously documented intermediary frictions and regulations. This helps reconcile with the existing explanations in the CIP literature. It also 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 investors 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 reflect institutional details of collateralization in the derivative contracts via a direct collateral channel that is independent of the previously documented intermediary frictions.

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.

[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.

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:

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

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 collateralization 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. As a result, measuring the CIP deviation necessitates explicit knowledge of the risk-free rates used to discount future cash flows in each currency, as well as costless counterparty risk hedging, 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 monitoring 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 derivative instruments 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 reflecting is simply risks of exchanged mechanical Libor cashflows.

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 in more detail in Chapter I Appendix A.

4 Empirical Strategy

4.1 Defining a Collateral Rental Yield

I define a simplified measure of the cost of collateralization applicable to the marginal investor in the FX forward and cross currency market. I rationalize it by assuming continuous full cash collateralization, which means that counterparties continuously need to post cash collateral in the full amount of their FX derivative contract's current MtM until expiration.[5]

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 on this collateral account differs from the risk-free rate. Hence, I define the following important single-currency collateral opportunity cost rate:

$$y_t = r_t - o_t \tag{4}$$

where r_t and o_t are the time t *risk-free rate* and CSA specified *contractual collateral rate*, respectively. A common market practice, under a standard ISDA CSA, is for o_t to 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_t, while paying a contractual collateral rate, o_t, to the collateral payer, keeping the difference between the two. However, from the viewpoint of a

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

collateral payer, it can be considered as collateral funding cost as the reverse is the case.[6]

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:

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

where

$$y_t^i = r_t^i - o_t^i \qquad y_t^\$ = r_t^\$ - o_t^\$ \tag{6}$$

which represents the difference in collateral opportunity costs between currency (*i*) and ($). The above identity is applicable for the case when rates are deterministic and in a discrete single-period time setting. Throughout the paper, I use this simplified definition of the measure, which I call collateral rental yield, to analyze the CIP violations.

4.2 Empirical Measure of CIP Violation

4.2.1 Short-term Horizon CIP Violation

The textbook CIP condition from (1) states that the FX forward contract is:

$$F_{t+1} = S_t \times e^{r_{t+1}^\$ - r_{t+1}^i} \tag{7}$$

Furthermore, the previously defined measures of collateralization in each currency in Eq. (6) were:

$$r_{t+1}^i = y_{t+1}^i + o_{t+1}^i \qquad r_{t+1}^\$ = y_{t+1}^\$ + o_{t+1}^\$ \tag{8}$$

[6]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 formulation I use the risk-free rate as the net return after hedging these risks, assuming that hedging is costless.

As a result, when a single currency, such as the domestic currency ($), is required as collateral and interest rates are deterministic, the collateralized FX forward price in a one-period setting at time t can be expressed as follows by substituting for the above Eq. (8) into Eq (7):

$$F_{t+1} = S_t \times e^{(y^{\$}_{t+1}+o^{\$}_{t+1})-(y^{i}_{t+1}+o^{i}_{t+1})} \tag{9}$$

Finally, substituting the defined cross-currency collateral rental yield from Eq. (5) to Eq. (9):

$$F_{t+1} = S_t \times e^{o^{\$}_{t+1}-(o^{i}_{t+1}+y^{i/\$}_{t+1})} \tag{10}$$

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

$$\begin{aligned} x^{adj}_{t+1} &= \left[o^{\$}_{t+1} - (o^{i}_{t+1} - (f_{t+1} - s_t))\right] - y^{i/\$}_{t+1} = 0 \\ &= x^{i,OIS}_{t+1} - y^{i/\$}_{t+1} = 0 \end{aligned} \tag{11}$$

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

Furthermore, because of the continuous MtM-ing feature and collateral posting in a single currency, such as US dollars, the illustration becomes slightly more complicated in a multi-period case because the collateral posting and collateral rental yield are stochastic. However, this case follows the same logic as the simplified single period case described above I refer the reader to frameworks such as Fujii and Takahashi (2012) Fujii and Takahashi (2013), Fujii, Shimada, Takahashi (2010a), Brigo, Capponi, and Pallavicini (2014), and Johannes and Sundaresan (2007) that model such stochastic collateralization features.

It is worth noting that in the stochastic multi-period case, the earlier defined collateral rental yield in (5) and (9) must be adjusted for a change in currency measure.[7] This is because, in a multi-period setting, if we have daily MtM that must be paid in US dollars, the counterparty with a negative MtM must fund the MtM in its own currency at the risk-free rate, convert the funds to US dollars, place them in the collateral account, and receive US dollar collateral rate remuneration (which is the OIS rate based on the CSA agreement). This is done continuously. The collateral receiver is the polar opposite. As a result, each counterparty faces daily exchange rate risk on the collateral account as the MtM fluctuates, necessitating a change of measure when pricing FX derivatives that are collateralized in a single currency, such as the US dollar.

[7] It can be represented by:

$$y^{i/\$}(s) = E_t^{Q^i}[(y^i(s)ds] - E_t^{Q^\$}[y^\$(s)ds] = E_t^{Q^i}[(y^i(s) - y^\$(s))ds] \tag{12}$$

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 (\$) respectively, where the money market account of each currency respectively is used as a numeraire.[8] Notice that I am changing the measure using the Radon-Nikodym density:

$$\frac{dQ^\$}{dQ^i}|_t = \frac{\beta_t^\$ S^{(i/\$)}(0)}{\beta_t^i S^{(i/\$)}(t)} \tag{13}$$

where $S^{i/\$}$ is the spot FX rate in terms of the domestic currency (\$) per unit of foreign currency (i).

4.2.2 Long-term Horizon CIP Violation

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 violation based on Libor (Libor-based CIP violation) does not involve any calculations and is given by the spread on the standard Libor xccy basis swap since the swap is viewed as a series of short-term FX forwards. If this Libor xccy basis spread is zero, then there is no violation of the CIP condition.

Due to the presence of collateralization, however, the structure of a standard Libor xccy basis swap cannot be viewed as a series of FX forwards and thus as a measure of CIP violation without some modifications. Libor xccy basis swaps have a non-linear payoff in Libor interest because they exchange Libor-indexed cashflows, which are then discounted to present value at the contractual collateral remuneration rates (OIS). To have zero CIP violations, the Libor and OIS rates must be equal to each other and be risk-free.[9] However, Libor and OIS rates are uncollateralized and, in practice, neither are risk-free or equal to each other. As a result, even if the OIS discount rates are risk-free, the Libor xccy basis may end up being non-zero, falsely signaling a violation of the CIP conditions; however, it will simply be reflecting mechanically the dynamics of the specific Libors' index cashflows (e.g., credit, liquidity, etc.) because those are the cashflows exchanged by the standardized contract terms of the xccy swap.

To avoid this situation, I must parse the Libor cash flows, replace them with OIS rate indexed cash

[9] Another possibility is that the Libor-based xccy basis equals zero if the Libor and OIS rates in each currency are equal. However, this does not imply that the CIP violation is zero. Again, for this to hold, the Libor and OIS rates must not only be equal, but they must also be risk-free. Also, 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.

flows, and recalculate the prices of the xccy basis swaps. As a result, I will be able to measure the CIP violations in the same standardized manner as for the short-term case earlier, as I will be able to consider the xccy basis swaps as a series of short-term FX forwards.

Therefore, rather than using the standard annualized continuously compounded Libor-based xccy basis below:

$$x_{t+1}^{i,Libor} = (IRS_{t+1}^{\$,Libor} - \left(IRS_{t+1}^{i,Libor} - (f_{t+1} - s_t)\right) \tag{14}$$

as a measure of long-term CIP violations, I will instead use the annualized continuously compounded OIS-based xccy basis shown below:

$$x_{t+1}^{i,OIS} = (IRS_{t+1}^{\$,OIS} - \left(IRS_{t+1}^{i,OIS} - (f_{t+1} - s_t)\right) \tag{15}$$

where log of 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 foreign currency. IRS^{Libor} is the Libor-indexed floating to fixed interest rate swap (IRS) to swap floating Libor cashflows into fixed rate cash flows in a single currency and IRS^{OIS} is the OIS-indexed floating to fixed IRS to swap floating OIS cash flows into fixed rate cashflows in a single currency.

The price of a OIS-based xccy basis swap now involves going long an OIS-based loan in one currency (e.g. domestic currency leg), while simultaneously going short an OIS-based loan in a foreign currency (e.g. foreign currency leg) that is exchanged at the current spot FX exchange rate (market condition). Chapter I Appendix B illustrates the procedure I follow to first extract the Libor and OIS yield curves from market prices of Libor xccy, IRS, and OIS swaps and then to recalculate OIS-based xccy basis swap prices by replacing the Libor-indexed cashflows with OIS-indexed cashflows. Thus, I create synthetically calculated OIS-based xccy basis swap prices. Figure 3 further illustrates the cash flows of a collateralized OIS-based xccy basis swap.[10]

Overall, the discussion above explains how the collateral currency (e.g., US dollar), MtM collateralization, and the wedge between the non-market collateral remuneration rate and the risk-free rate affect the price of FX forwards and xccy swaps and how this changes how we can measure CIP violations.

4.3 Empirical Proxies for the Collateral Rental Yield

To evaluate the impact and contribution of collateralization to the xccy basis, and thus contribution to CIP violations, I obtain empirical estimates of the collateral rental yield embedded in the pricing of FX forwards and xccy swaps. I study the CIP violation over both the short and long-term horizons; the same measure applies to the short-term OIS-based xccy bases and the long-term synthetic OIS-based xccy bases calculated by replacing Libor-indexed cashflows with OIS-indexed cash flows.

Moreover, 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

[10]Furthermore, Chapter I Appendix B shows closed form pricing derivations for xccy swaps when the collateral posting and collateral rental yield are stochastic due to the continuous MtM-ing feature. I also refer the reader to frameworks such as Fujii and Takahashi (2012) Fujii and Takahashi (2013), Fujii, Shimada, Takahashi (2010a), Brigo, Capponi, and Pallavicini (2014), and Johannes and Sundaresan (2007) for more information on pricing exchange rate and interest rate swaps with stochastic collateralization features.

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 follows:

$$y^{i/\$}_{n,gc} = (r^{i}_{n,gc} - o^{i}_{n}) - (r^{\$}_{n,gc} - o^{\$}_{n}) \tag{16}$$

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:

$$y^{i/\$}_{tbill} = (r^{i}_{tbill} - o^{i}_{3m}) - (r^{\$}_{tbill} - o^{\$}_{3m}) \tag{17}$$

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:

$$y^{i/\$}_{BOX} = (r^{i}_{tbill} - o^{i}_{3m}) - (r^{\$}_{BOX} - o^{\$}_{3m}) \tag{18}$$

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).

4.4 Residual Counterparty Credit Risks and Intermediary Frictions

Every counterparty in the OTC market is inclined to reflect their own funding, counterparty credit risk, or investment conditions, rather than the risk-free rate conditions when pricing and trading FX forward and xccy basis contracts. In determining the risk-neutral collateral rental yield, I used the risk-free rate conditions to identify the cost of collateralization as frictionless and distinct from the aforementioned costs or risk-based returns. However, empirically, this will be the case only if the proxies chosen for the risk-free rate truly reflect the theoretical risk-free rate conditions, which means they are not affected by any of the other conditions mentioned, such as counterparty funding conditions or credit risk conditions, as well as any other intermediation frictions.

Because the FX forward and xccy markets are not completely collateralized in practice, it is natural to expect that there will be residual credit or counterparty risk premiums that will be priced in the aggregate FX forward and xccy contracts. This will be especially pronounced for short-term deviations from the CIP because the less than three-month FX forward market is less collateralized than the longer-dated market. As a result, the empirical analysis that follows, I account for and control for any remaining counterparty credit risk, as well as other balance sheet and regulatory intermediation frictions that could affect not only the FX forward and xccy prices directly, but also the proxies used in this study for the risk-free rate. This approach also allows me to establish evidence on the presence of a direct collateral channel that is independent of global risk factors, balance sheet constraints, and regulatory frictions documented in the literature so far that affects CIP violations.

I further describe the data before presenting the results and their implications for the CIP violations.

5 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. (Chapter I Appendix E provides further information on the data.)

Finally, I also obtain transactional data on xccy basis swap derivatives trades (459,143 reports) executed between January 1, 2013 and March 31, 2020, which are publicly distributed by the Depository Trust & Clearing Corporation (DTCC) Data Repository (U.S.) LLC (DDR). On December 31, 2012, the Commodity Futures Trading Commission (CFTC) implemented mandatory real-time reporting and public dissemination of OTC swap trades as part of the Dodd-Frank Wall Street Reform and Consumer Protection Act. Swap transactions must be reported to a record-keeping facility known as a swap data repository (SDR), which then disseminates transaction details to the public (e.g., trade price, trade size, timestamp, and trade characteristics[11] related to the Dodd-Frank reforms).

[11] DDR's Real Time Dissemination Dashboard User Guide provides a complete list of data fields in publicly disseminated trade reports (https://pddata.dtcc.com/gtr/cftc/dashboard.do).

6 Results

6.1 Prevalence of Collateralization

Figure 4 reports the level of collateralization in the xccy basis market based on transactions data from the DTCC Data Repository. Panel A presents the distribution across the different types of transaction collateralizations for the total sample period between 2013-2020. A massive 76.68% of the xccy basis swap transactions are backed by some form of collateralization. Specifically, 26.2% are fully collateralized which means that require counterparties to post initial and variation margin (FC), 47.6% require counterparties to provide variation margin only (PC), and 2.1% of the sample requires only one of the counterparties to post margin. About 24.1% of the transactions are uncollateralized (UC).

Furthermore, Panel B zooms in on these collateralization compositions over time, and it is evident that the share of collateralization increased over the years, while the share of uncollateralized trades gradually decreased, from 44.8% in 2013 to only 3.8% in 2020. In particular, the share of fully collateralized (FC) trades increased the most from 10.4% in 2013 to 59.7% of all cross-currency swap transactions in 2020.

Finally, the proportion of trades in the sample that are not cleared through a clearing house is 99.7%. This suggests that the clearing status does not really correlate with the evidenced increase in collateralization over time. Hence, the central clearing, which is supposed to be an effective way to reduce counterparty risk is not at play in this asset class derivatives market.

6.2 Short-Term Collateral-Adjusted CIP Violations

Recalculating the CIP violation while adjusting for the collateral rental yield in Eq. (11) across various proxy measures, called "collateral-adjusted xccy basis", reveals a substantial reduction in the magnitude of the CIP violations when compared to measurement approaches that ignore a collateral rental yield, i.e., that do not adjust for collateral opportunity costs. Table 1 provides the mean and standard deviation of the unadjusted versus collateral-adjusted CIP violations across tenors from 1-week to 3-months 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"). Similar to Du and Schregner (2021), the Crisis sub-periods include August 2008 - December 2009 (GFC), November 2011 - February 2012, and March 2020 - May 2020 (Covid), and the Post-Crisis sub-period runs from January 1, 2010 to May 31, 2020 and excludes the Crisis sub-period.

In the tranquil Post-Crisis sample period, the collateral adjustment to the short-term 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, and 10 basis points for the 3-month T-bill-adjusted xccy basis. It even makes the BOX-adjusted collateral xccy basis become positive by about 7 basis points. Taken together, these results equate to between one-third to complete, or on average, across tenors and measures, about a two-third reduction in the magnitude of the OIS-based CIP deviation due to collateral adjustment.[12]

During the Crisis sample period, however, the collateral-adjusted xccy basis is not significantly different from the OIS-based xccy basis, with the exception of the BOX-based collateral adjustment. This suggests that the BOX-based collateral rental yield captures additional financial and economic stress factors that are present during crises. Overall, in times of crisis, however, the

[12] 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).

results suggest that collateralization becomes of secondary importance for FX forward prices.

In terms of cross-sectional evidence, 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 across different proxies. The cross-sectional relationship works particularly for the GC-based collateral rental yield.

Turning to formal tests, Table 2 shows results from panel regressions of the short-horizon OIS-based xccy basis, x_n^{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[13], 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, especially for the 1 and 3-months horizon regressions.

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

[13] Especially for GC rates, for example.

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.

Moreover, the coefficient estimates for the collateral rental yield are similar in magnitude between the three proxies. Therefore, the 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 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 counterparty and funding 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 funding and 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 credit 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 violations 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 violations. 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 sheet constraints binding 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 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 narrative, 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[14] created by the US Federal Reserve System, is significant across specifications apart 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, this study's narrative 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.

It is worth noting that, according to the study's collateralization but no-arbitrage narrative, the strength of the US dollar should affect the xccy basis only through the collateral channel and thus be absorbed by the collateral rental yield measure. Based on this hypothesis, it should not appear as significant here separately if no-arbitrage is maintained. However, for the empirical analysis, I use simple proxies for the collateral rental yield that do not entail a change in measure between the bilateral currencies, reflecting the institutional features that the collateral is MtM continuously

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

and denominated in US dollars. Thus, the strength of the US dollar covaries with the xccy basis independently of collateral rental yield proxies.

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 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 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 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.

6.3 Long-Term Collateral-Adjusted CIP Violations

Majority of xccy basis swaps traded in the market are based on Libor. However, as discussed in Section 4.2.2, in order to analyze the CIP violations consistently across tenors, the xccy basis swaps must be OIS-based. OIS-based xccy swaps exist but they are not liquid or readily tradeable in the market, and they are available only in few currencies, so there is no consistent data on them. As a result, I generate OIS-based xccy basis swap prices by parsing the mechanical Libor-index risk embedded in the market prices of Libor-based xccy basis swaps. I compute a synthetic OIS-based xccy swap price using Eq. (15) as described in Section 4.2.2 and Chapter I Appendix B.[15] This allows me to analyze CIP violations across tenors in an appropriate and consistent manner, while avoiding contamination from mechanical Libor-indexed cash flows.

To show the importance of this particular detail, Figure 6 compares the synthetic OIS-based xccy swap basis to the Libor-based xccy swap basis for each currency pair's 3-month, 1-year, 5-year, and 10-year tenors. Observe that the OIS-based xccy swap basis is much smaller across the term structure for all currency pairs, with the reduction being more pronounced for the long horizons (> 3-months). Because xccy basis swaps above 3-month tenors exchange mechanical Libor-indexed cashflows, parsing out these cashflows and replacing them with OIS-indexed cashflows reduces the portion of the xccy basis attributable to purely mechanical factors, such as swapping contractually market standardized Libor cashflows.

Turning to formal empirical tests, Table 4 presents panel regression results from regressing the synthetic OIS-based xccy swap basis on three different proxies for the collateral rental yield (GC-based in Panel A, T-bill-based in Panel B, and BOX-based in Panel C) and other factors from the empirical literature for 1-year to 10-year tenors. It includes specifications wherein all variables are in levels. If the proxy collateral rental yield effectively measures collateral costs and the xccy basis swaps market as a whole is perfectly and fully collateralized, the framework suggests a slope

[15] A simpler method would be to combine a Libor-based currency basis swap with Libor-OIS swaps in each bilateral currency. The end result will be an OIS-based xccy basis swap. However, because Libor-OIS swaps are not available in every currency in the sample and are not very liquid, I chose to use the more involved procedure of creating synthetic OIS-based xccy swap prices.

coefficient of 1 (because the synthetic xccy swap prices are OIS-based). However, given that the xccy swap market is not fully collateralized in practice, there are still counterparty credit risk premia, and the proxies for the collateral rental yield are composed of short-term rates (due to a lack of data on matched tenor proxies), I would expect the coefficient to be less than one.

Table 4 shows that for each horizon, the coefficient on each proxy for the collateral rental yield is less than one, but still as high as one half, and statistically significant. The collateral rental yield is associated with a more negative xccy basis, which is economically significant. The magnitude of the coefficient estimates is similar across the three proxies and decreases as the tenor increases. The magnitude decrease is expected given that the tenor mismatch between the OIS-based xccy basis and the proxy measures for the collateral rental yield increases as the horizon increases because the short-term proxy does not capture perfectly the whole term structure. This also explains why the R^2 is small.

The remaining contribution to the variation in the xccy basis is due to the Libor-OISs spread because of residual counterparty credit risk (not related to mechanical Libor cashflows) because the xccy basis swaps market, while heavily collateralized, is not exactly fully collateralized. The strength of the US dollar has an independent contribution to the xccy basis here, as it did in the previous short-term basis analysis. Naturally, the same reasoning applies. The collateral rental yield proxies do not involve a change in measure between the bilateral currencies, reflecting the fact that the collateral is MtM continuously and denominated in US dollars. As a result, the effect of the collateral's required US dollar currency denomination is not absorbed in the collateral rental yield and appears to affect the xccy basis outside of it, as per the proposed hypotheses in this study. Other intermediary frictions and regulatory constraints, including the regulatory year-end, leverage, and capital factors, are also persistently related to the long-term synthetic OIS-based xccy basis across the tenors independently of the collateral rental yield, which is in line with the existing empirical evidence (Cenedese, Corte, and Wang, 2020; Du, Tepper, and Verdelhan, 2018; Baba and Packer, 2009a, 2009b). Despite the inclusion of these factors in the regressions, the collateral rental yield proxies remain significant, indicating that collateral affects xccy base prices through an independent and direct collateral channel.

In sum, the above analysis shows that collateral rental yield proxies are significant and help to explain long-term OIS-based CIP violations on average across tenors. Compared to the analysis on the short-term CIP violations, the results on the long-term CIP violations show that the intermediary frictions have independent effects on the CIP, suggesting that the collateral rental yield affects the CIP independently of these frictions, which I investigate in more detail next.

6.4 Global Risks, Intermediary Frictions, and The Collateral Channel

The literature has related the CIP violations to global risks and frictions facing intermediaries (e.g., Cenedese, Corte, and Wang, 2020; Avdjiev, Du, Koch, and Shin, 2019; Du, Tepper, and Verdelhan, 2018; Sushko, Borio, McCauley, and McGuire, 2016; Baba and Packer, 2009a, 2009b). To understand if there is evidence that these risks and frictions affect the CIP violations via a collateral transmission channel, Table 5 shows panel regression results from regressing the each of the proxy collateral rental yield on several counterparty and global risk proxies as well as on intermediary 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 the GC-based collateral rental yield is statistically significant and systematically larger for contracts that cross year-end reporting dates. The GC-based collateral rental yield is on average 6.4 basis points more expensive on year-end across tenors. Apart from the BOX-based collateral rental yield, the HKM regulatory leverage and capital factors are not significant across proxies, indicating that leverage and capital regulation do not affect directly the collateral funding costs (the AEM leverage factor was tested and because it was insignificant was removed due to limited number of quarterly observations).

Furthermore, the US Libor-OISs spreads are significant for both the T-bill and BOX-based collateral rental yields but not for the GC-based collateral rental yield suggesting that the T-bill and BOX-based proxies capture residual counterparty credit risks or general credit conditions in the economy, and that they are relatively poorer proxies for the true and frictionless theoretical risk-free rate. Instead, GC repo rates appear to be superior proxies for the risk-free rate.

The result that the collateral rental yield is not persistently related to proxies for intermediary frictions 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. However, in practice, there is no single risk-free rate, the market is not fully collateralized, and regulatory frictions are unavoidable. Furthermore, the proxies used to calculate the risk-free rate are imperfect. As a result, the analysis suggests that it is plausible that the collateral not only directly and independently affects the prices of xccy basis, but that it can also be affected by some of the same factors that affect these xccy prices separately. In other words, the collateral is not completely frictionless.

Furthermore, the results that the collateral rental yield does not covary with the strength of the US dollar, despite the fact that it should based on the framework due to the need to post US dollar collateral, are supported empirically here because the simple proxies for the collateral rental yield do not entail a change in measure in the bilateral currencies. However, the log FX volatility and exchange rate, and forward FX bid-ask spread liquidity frictions appear to affect the collateral rental yield, albeit not consistently across proxies.

Overall, the collateral rental yield is related to the CIP violations directly and independently via a direct collateral channel; however, it can covary with measures of residual counterparty credit and funding risk, as well as the regulatory intermediary frictions. These frictions also affect the CIP violations independently of the collateral rental yield.

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 opportunity costs and currency to be consistent with no-arbitrage laws.

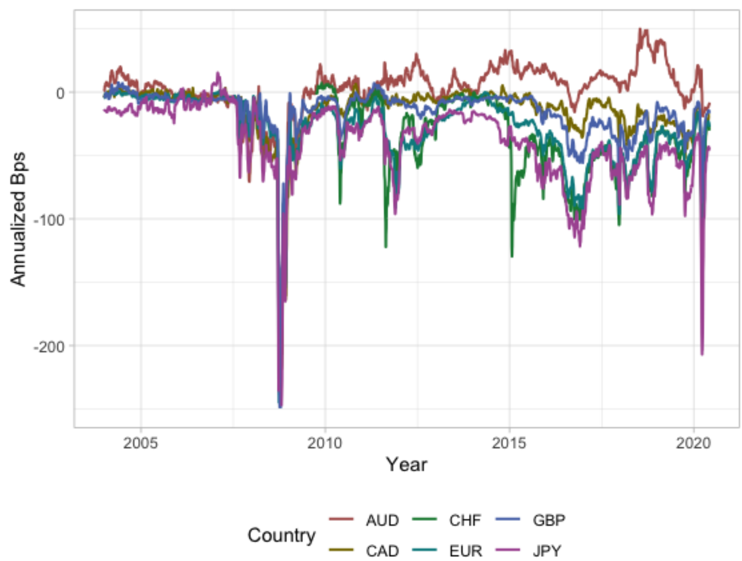
Furthermore, the results suggest an important collateral channel through which costly collateralization contributes directly and independently to explaining standard CIP violations. The evidence shows that the documented collateral channel is independent of some of the previously documented global risks and intermediary frictions, which also contribute to explaining the standard CIP violations. This helps reconcile with the existing explanations in the CIP literature. 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.

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.

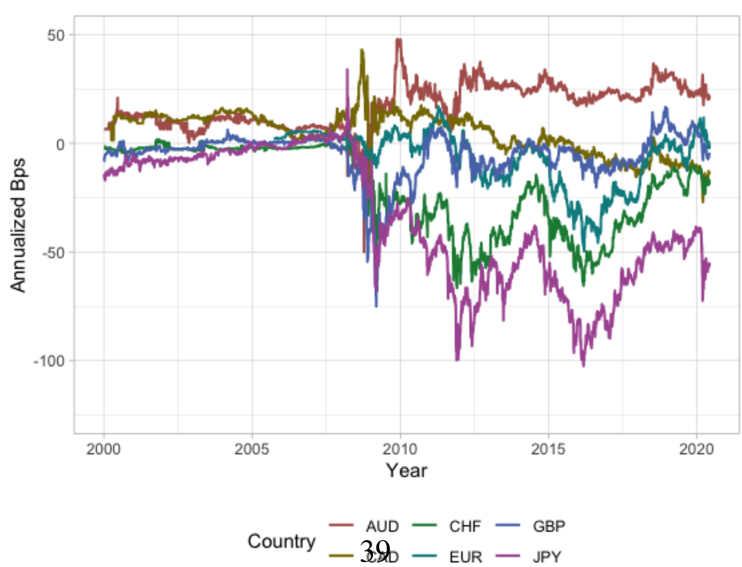


Figure 2: Cash Flow Diagram for Standard CIP Arbitrage in US dollars

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-collateralized forward contract.

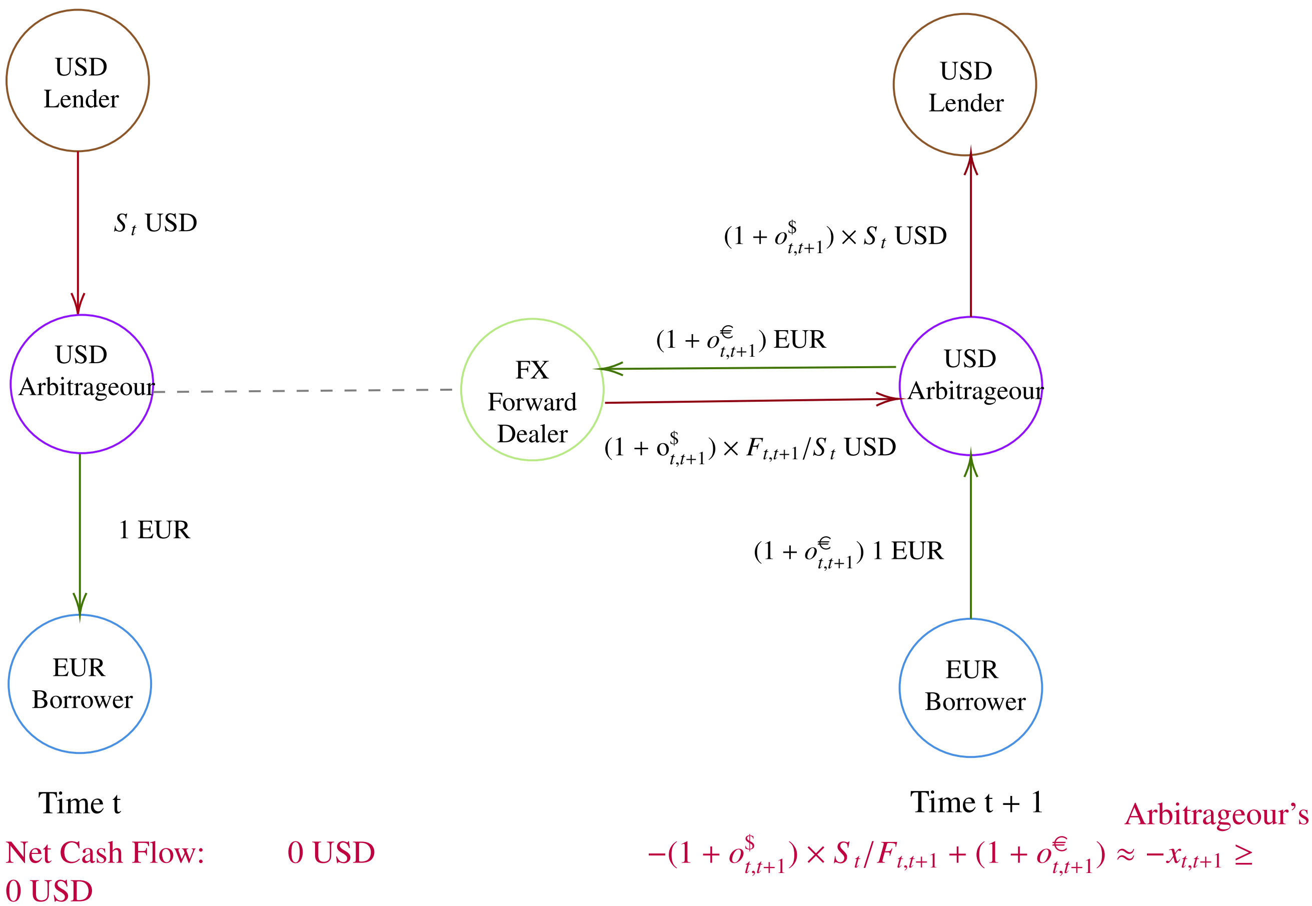


Figure 3: Cash Flows of a Collateralized OIS-Based Cross Currency Basis Swap

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 OIS $O^{\$}(T_{n-1}, T_n)$ 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 OIS plus the xccy basis ($O^{€}(T_{n-1}, T_n) + x_n$) 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.

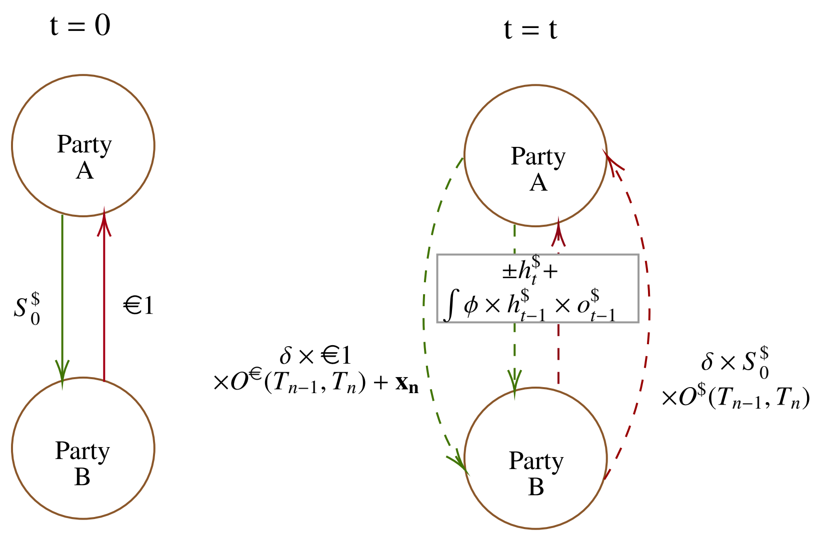
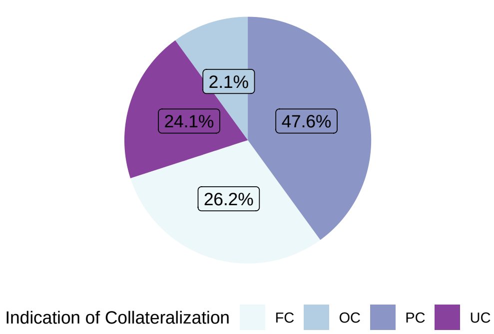


Figure 4: Composition of Collateralization

This figure reports the level of collateralization in the reported executed xccy basis trades between January 1, 2013 and March 31, 2020, which are publicly distributed by the Depository Trust & Clearing Corporation (DTCC) Data Repository (U.S.) LLC (DDR). Fully collateralized (FC) require counterparties to post initial and variation margin, partially collateralized (PC) require counterparties to provide variation margin only (PC), one-way collateralized (OC) require only one of the counterparties to post margin, and uncollateralized (UC) does not require any margin posting. Panel A presents the distribution of reports across different types of transaction collateralizations for the total sample period between 2013-2020 while Panel B zooms in on these collateralization compositions over time.

(A) Full Sample 2012 - 2020



(B) Collateralization by Year

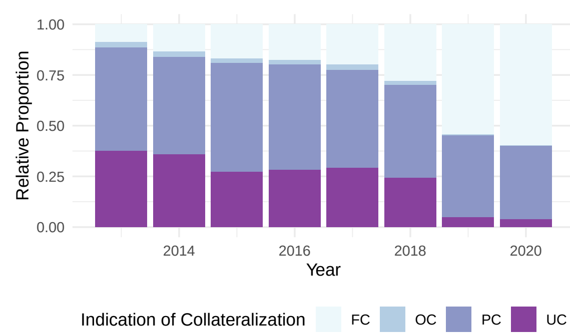


Figure 5: Cross-Section of Currency Basis and Collateral Rental Yield (2009-2020)

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 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; and 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. 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).

Short-Term OIS-based CIP - 3-month horizon.

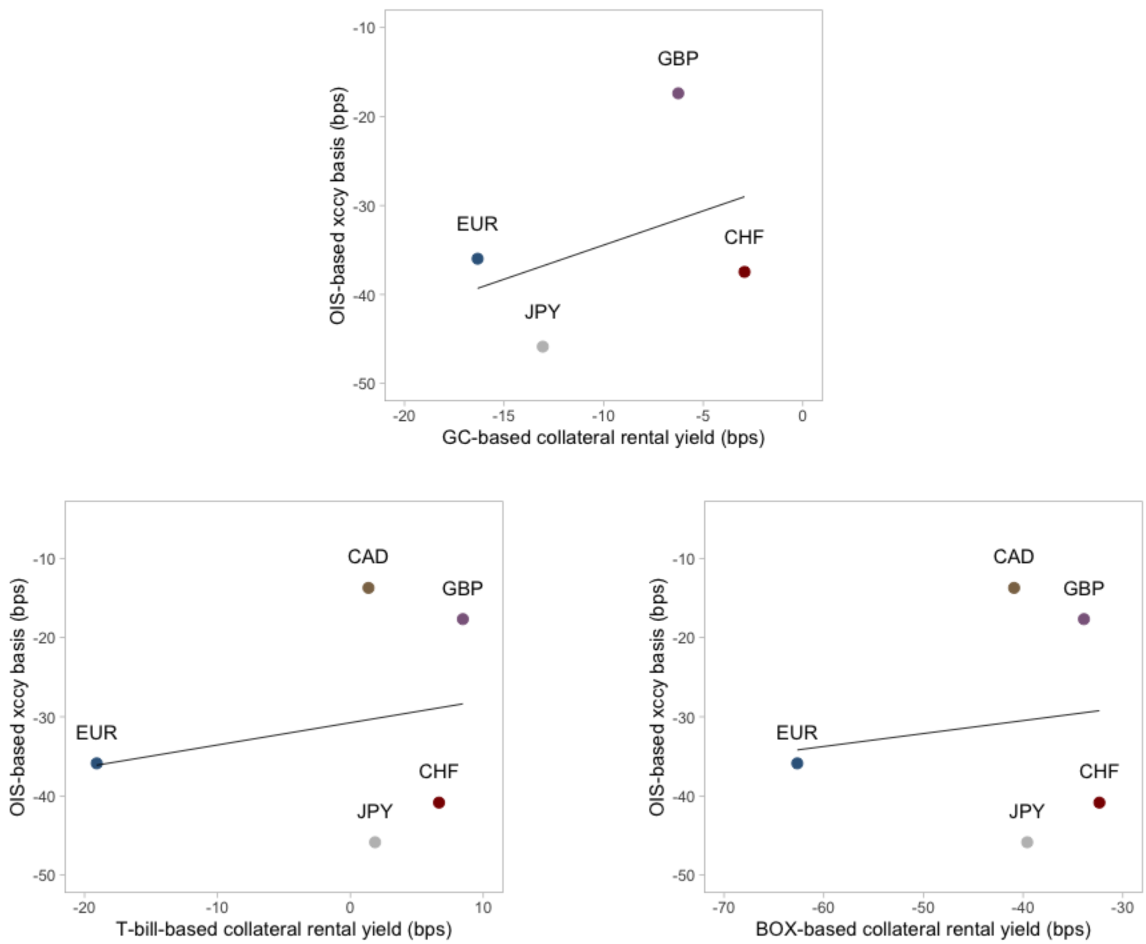
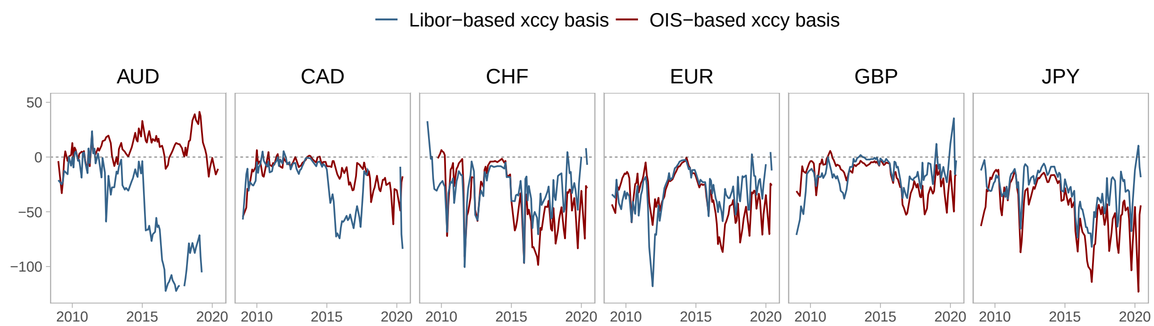


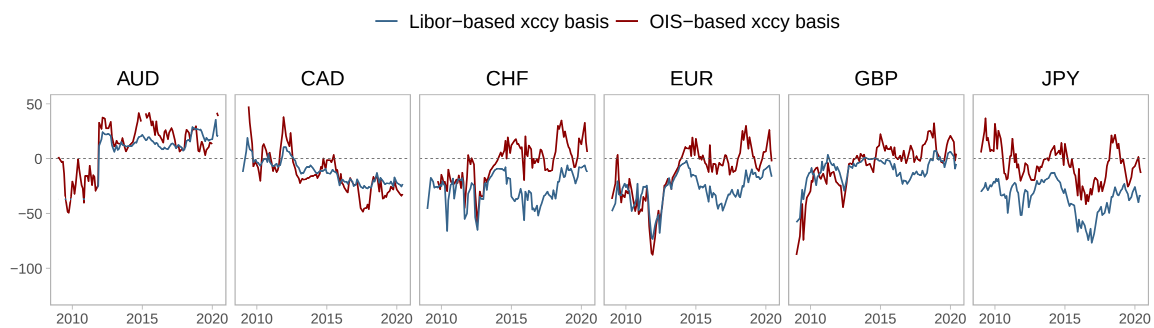
Figure 6: Standard Libor Versus OIS-Based CIP Deviations

This figure shows the monthly Libor-based xccy basis versus the OIS-based 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 OIS-based xccy basis stands for the re-calculated xccy basis following the procedure in Chapter I Appendix B.

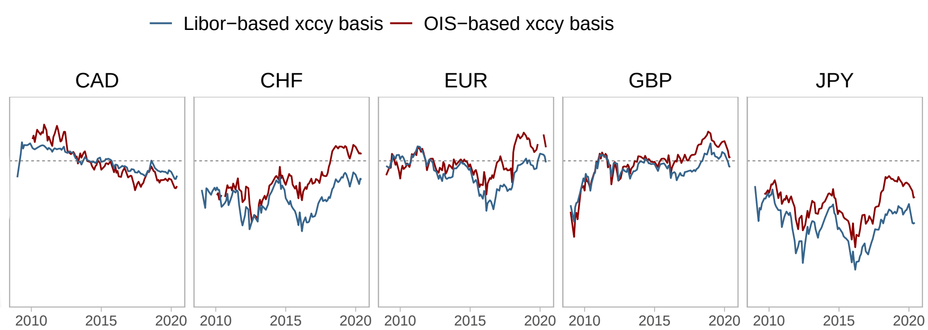
Panel A: 3-month Horizon.



Panel B: 1-year Horizon



Panel C: 5-year Horizon



Panel D: 10-year Horizon

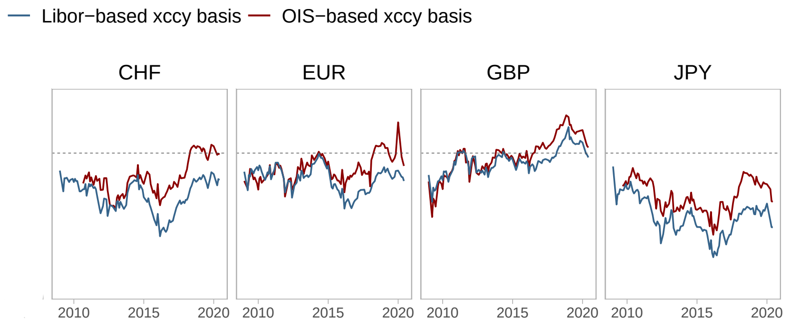


Table 1: Short-term OIS-based vs. Collateral-Adjusted CIP Deviations

This table reports the mean of daily short-term OIS-based xccy basis 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 n stands for $1w$ (1-week), $1m$ (1-month), and $3m$ (3-month); $x^{adj}_{n,gc}$ 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; and $x^{adj}_{3m,BOX}$ 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. 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).

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

Table 2: Regressions for Short-Term OIS-based Xccy Basis on Observable Collateral Proxies

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)
$y_{n,GC}^{i/\$}$	1.10***	0.91**	1.42***	1.23***	0.51***	0.18***				
	(0.38)	(0.36)	(0.32)	(0.22)	(0.11)	(0.07)				
$y_{3m,Tbill}^{i/\$}$							0.56***	0.50***		
							(0.06)	(0.05)		
$y_{3m,BOX}^{i/\$}$									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)
LiborOIS s		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)
$\Delta y^{i/\$}_{n,GC}$	0.52***	1.12***	0.81**	0.54**	0.34**	0.12**				
	(0.12)	(0.16)	(0.36)	(0.22)	(0.13)	(0.04)				
$\Delta y^{i/\$}_{3m,Tbill}$							0.39***	0.37***		
							(0.08)	(0.08)		
$\Delta y^{i/\$}_{3m,BOX}$									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)
$\Delta LiborOIS\,s$		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 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: Regressions for Long-Term Synthetic OIS-Based Xccy Basis

This table shows panel regression results for the monthly level in the synthetic OIS-based xccy basis (dependent variable), x_n^{OIS}, on the level proxy for the GC-based collateral rental yield $y^{i/\$}_{3m,GC)}$ (Panel A), for the T-bill-based collateral rental yield $y^{i/\$}_{3m,Tbill)}$ (Panel B), and for the BOX-based collateral rental yield $y^{i/\$}_{6m,BOX)}$ (Panel C) expressed in basis points, and other controls in the period between 1 January 2009 and 31 May 2020. 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); $LiborOIS\,s$, 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: *For GC-based collateral rental yield proxy (in levels).*

	Dependent variable: x_n^{OIS}					
	1-year xccy basis		5-year xccy basis		10-year xccy basis	
	(1)	(2)	(3)	(4)	(5)	(6)
$y_{3m,GC}^{i/\$}$	0.41***	0.19***	0.44***	0.21***	0.34***	0.25***
	(0.07)	(0.06)	(0.09)	(0.08)	(0.05)	(0.10)
$Yend$		−6.28***		−3.12		−1.61
		(2.18)		(2.20)		(2.31)
$HKM\ leverage$		−0.02**		−0.05***		−0.04***
		(0.01)		(0.01)		(0.01)
$HKM\ capital$		−19.27**		−41.65***		−35.35***
		(9.65)		(11.97)		(12.72)
$LiborOIS\,s$		−0.05		−0.16**		−0.14*
		(0.06)		(0.07)		(0.07)
$US\ \ factor$		−0.26***		−0.65***		−0.72***
		(0.11)		(0.23)		(0.29)
$\Delta lnFX$		−16.69		−17.57		−15.50
		(19.52)		(19.60)		(21.09)
$lnVol$		−10.23***		−8.30**		−5.33
		(3.89)		(3.83)		(4.06)
$FXbidask$		23.14*		19.87*		26.43**
		(12.00)		(10.78)		(12.39)
$lnVix$		−8.58**		−3.38		−1.05
		(3.84)		(3.82)		(4.03)
Currency pairs	4	4	4	4	4	4
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Within Adj-R^2	0.01	0.11	0.01	0.22	0.01	0.13
Observations	344	264	335	257	331	253

PANEL B: *For Tbill-based collateral rental yield proxy (in levels).*

	Dependent variable: x_n^{OIS}					
	1-year xccy basis		5-year xccy basis		10-year xccy basis	
	(1)	(2)	(3)	(4)	(5)	(6)
$y_{3m,Tbill}^{i/\$}$	0.46***	0.42***	0.45***	0.43***	0.36***	0.28***
	(0.08)	(0.09)	(0.09)	(0.11)	(0.07)	(0.08)
$Yend$		−6.12***		−4.38**		−3.17
		(1.94)		(1.91)		(2.07)
$HKM\ leverage$		−0.01**		−0.03***		−0.03***
		(0.01)		(0.01)		(0.01)
$HKM\ capital$		−17.73**		−25.84**		−28.83**
		(8.34)		(10.52)		(11.38)
$LiborOIS\,s$		−0.08		−0.18***		−0.07***
		(0.06)		(0.03)		(0.03)
$US\ factor$		−0.36**		−0.74***		−0.85***
		(0.18)		(0.29)		(0.30)
$\Delta lnFX$		−34.53*		−25.16		−12.23
		(18.33)		(18.16)		(19.31)
$lnVol$		−6.80*		−2.80		−4.61
		(3.69)		(3.56)		(3.75)
$FXbidask$		29.81**		25.19**		26.45**
		(12.32)		(11.77)		(11.91)
$lnVix$		−9.59***		−5.79*		−5.00
		(3.57)		(3.42)		(3.75)
Currency pairs	5	5	5	5	4	4
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Within Adj-R^2	0.01	0.14	0.02	0.16	0.02	0.13
Observations	465	369	448	355	355	281

PANEL C: *For BOX-based collateral rental yield proxy (in levels).*

	Dependent variable: x_n^{OIS}					
	1-year xccy basis		5-year xccy basis		10-year xccy basis	
	(1)	(2)	(3)	(4)	(5)	(6)
$y_{6m,BOX}^{i/\$}$	0.52***	0.43***	0.49***	0.38***	0.46***	0.35***
	(0.09)	(0.10)	(0.08)	(0.08)	(0.09)	(0.10)
$Yend$		−4.19**		−2.74		−1.21
		(1.87)		(1.98)		(2.12)
$HKM\ leverage$		−0.02**		−0.04***		−0.03***
		(0.01)		(0.01)		(0.01)
$HKM\ capital$		−18.16**		−29.23***		−21.39*
		(9.99)		(10.72)		(11.48)
$LiborOIS\,s$		−0.09		−0.15***		−0.10**
		(0.07)		(0.04)		(0.05)
$US\ \ factor$		−0.41**		−0.87***		−0.93***
		(0.21)		(0.32)		(0.36)
$\Delta lnFX$		−40.50**		−20.80		−10.90
		(17.53)		(18.50)		(19.48)
$lnVol$		−0.72		−0.04		−1.62
		(3.64)		(3.76)		(3.93)
$FXbidask$		18.51		17.98		13.05
		(13.23)		(13.51)		(13.64)
$lnVix$		−3.40		0.23		2.09
		(3.90)		(4.01)		(4.33)
Currency pairs	5	5	5	5	4	4
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Within Adj-R^2	0.05	0.23	0.01	0.15	0.04	0.16
Observations	344	344	330	330	261	261

Table 5: Regressions for 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. 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); $LiborOIS\,s$, 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.*

	$y_{3m,GC}^{i/\$}$	$y_{Tbill}^{i/\$}$	$y_{BOX}^{i/\$}$
	(1)	(2)	(3)
$Yend$	-6.44^{***}	-1.87	-3.08
	(1.96)	(2.01)	(2.37)
$HKM\ leverage$	-0.01	0.01	-0.04^{***}
	(0.01)	(0.01)	(0.01))
$HKM\ capital$	1.23	3.15	-31.96^{**}
	(10.78)	(10.78)	(12.62)
$LiborOIS\,s$	0.11	0.13^{***}	0.28^{***}
	(0.23)	(0.04)	(0.04)
$US\ factor$	-0.22	-0.30	-0.39^{**}
	(0.25)	(0.26)	(0.16)
$\Delta lnFX$	-7.55	-15.11^{**}	-12.92^{*}
	(5.96)	(5.99)	(6.95)
$lnVol$	11.58^{***}	-4.41	-14.40^{***}
	(3.53)	(3.82)	(4.55)
$FXbidask$	-22.97^{**}	-28.76^{**}	-30.40^{*}
	(10.98)	(12.73)	(16.77)
$lnVix$	-8.91^{**}	0.65	-0.93
	(3.51)	(3.72)	(4.97)
Currency pairs:	4	5	5
Within Adj-R^2	0.16	0.02	0.26
Observations	264	369	344

PANEL B: *In Changes.*

	$\Delta y^{i/\$}_{3m,GC}$	$\Delta y^{i/\$}_{Tbill}$	$\Delta y^{i/\$}_{BOX}$
	(1)	(2)	(3)
$Yend$	-6.12^{***}	-2.88^{*}	-1.18
	(2.43)	(1.61)	(2.34)
$HKM\ leverage$	-0.001	0.01	0.01
	(0.01)	(0.01)	(0.01)
$HKM\ capital$	18.82	0.44	5.34
	(13.72)	(9.12)	(13.16)
$\Delta LiborOISs$	0.07	0.05	0.54^{***}
	(0.09)	(0.05)	(0.08)
$\Delta US\ factor$	-0.11	-0.22	-0.17^{**}
	(0.18)	(0.76)	(0.08)
$\Delta lnFX$	18.53	20.07	42.71^{*}
	(24.26)	(17.58)	(25.10)
$\Delta lnVol$	2.47	1.97	-18.69^{***}
	(5.64)	(3.88)	(5.58)
$\Delta FXbidask$	-13.77	-13.77^{**}	-26.00^{**}
	(8.70)	(6.72)	(11.16)
$\Delta lnVix$	-8.49^{**}	-3.43	0.38
	(3.61)	(2.44)	(3.89)
Currency pairs:	4	5	5
Within Adj-R^2	0.01	0.01	0.16
Observations	234	321	296

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CHAPTER II:
Sovereign Defaults and Currency Crashes: Insurance and Quanto

1 Introduction

When a sovereign defaults, it is natural to be concerned about other economic effects, most notably the attractiveness of the country's currency for debt repayments, international trade, and capital flows. As a result, an important question is whether sovereign defaults and severe currency depreciations such as currency crashes are related. Because these are rare disaster states of the world, estimating their covariance from scarce historical data is prohibitively difficult. I take a novel approach and propose and then estimate their relationship using prices of far out-of-the-money (FOM) foreign exchange (FX) options that identify currency crashes and prices of credit default swaps (CDS) that identify sovereign defaults. I then study their properties in the context of a no-arbitrage framework, which allows me to add discipline and contribute to better predictions about their relationship and implications for sovereign debt pricing and the carry trade.

I demonstrate that, under no-arbitrage and if currency crashes and sovereign defaults occur concurrently, a claim to a CDS is equivalent to a claim to a portfolio of FOM FX options. This is because both claims only pay in the same disaster state of the world where currency crashes coincide with sovereign defaults. Intuitively, FOM FX options reflect the market's assessment of the tail risk of a strong movement in the exchange rate, such as a currency crash, whereas a CDS is the market assessment (the CDS spread) of a sovereign default insurance that reflects the state of the local and global economies, as well as investor risk aversion (Longstaff et al. 2011). In addition, because of the identification using FOM FX options and the no-arbitrage design, I can disentangle the conditional covariance between currency crashes and sovereign defaults from the expected magnitude of the currency crash. This adds to the body of literature that has previously focused on estimating currency crash probabilities that are not independent of expected crash sizes.

I show that the prices of two claims, one on the CDS and one on the portfolio of FOM FX options, are strongly correlated, which suggests a strong relation between currency crash and sovereign default risks. At the same time, this relationship implies that the same sovereign should pay a lower credit interest rate on otherwise equal debt in local currency (LC) versus foreign currency (FC), a stylized fact known as the "quanto spread discount."[1] In addition, I find that the dynamic properties of the correlation between the two claims, as measured by a newly developed metric I refer to as "crash covariance risk," which is the covariance between the current foreign exchange rate's distance from a currency crash barrier and the default intensity, explains the empirical dynamics of the quanto spread discount and the carry trade.

A puzzling result emerges: the price levels of the two claims differ, interestingly during tranquil times, suggesting some form of segmentation between the credit and foreign exchange rate option markets during those times which vanishes during times of crisis when the two markets converge and start acting as if they were one. This discovery paves the way for future research. However, it suggests that either latent Peso risk premia is priced in the FOM FX options market, such as the risk of a currency crash in the absence of a sovereign default, which is extremely improbable in practice in developed countries, or that two distinct groups of investors price the same risk differently, with potential frictions impeding the ability to close this segmentation gap.

Before delving deeper into the connectivity framework and detailed empirical findings of these markets, I draw your attention to a few stylized facts. There is anecdotal evidence that the foreign exchange and sovereign credit markets are occasionally related, especially during distressed peri-

[1]Intuitively, an insurer requires a lower CDS default premium in LC because a positive correlation between credit default and currency crash means that, in the event of a default, the LC will likely depreciate, and thus the LC CDS insurance contract will pay a lower payoff when converted in terms of FC; thus it is cheaper than the FC CDS insurance premium.

ods.[2] As a result, understanding the covariance between these markets and how it evolves over time is critical. However, a measurement roadblock arises because currency crashes and sovereign defaults are rare disaster states of the world; as a result, insufficient data are available to researchers. Hence, rather than examining scarce historical data on rare disaster events, I take a novel approach. I identify the risk-neutral distribution of currency crashes using prices of FOM FX options that are directly related to these rare events. For the sake of brevity, a currency crash is defined here as the FX rate falling below a 10-delta strike barrier on a FOM FX option. I also learn about sovereign defaults from sovereign credit default swap (CDS) prices.

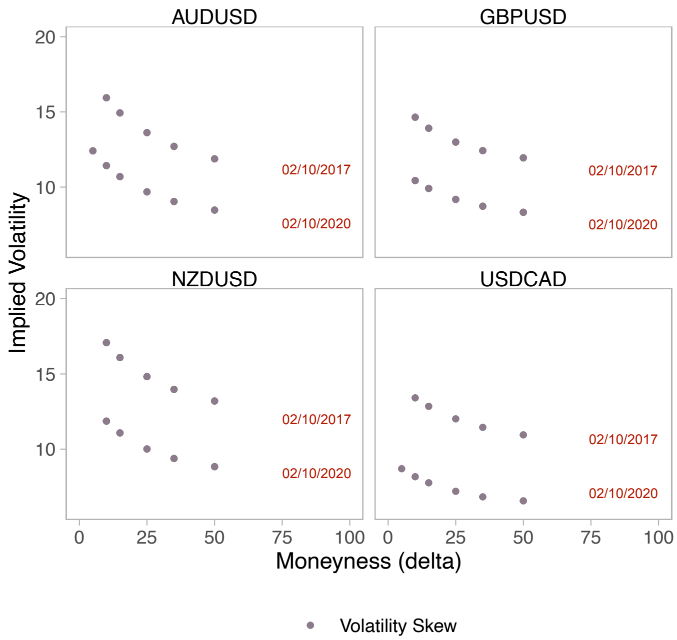
When a sovereign defaults on its foreign debt, the country's LC inevitably crashes in value, resulting in higher volatility, negative skewness, and fatter tails in the conditional distribution of exchange rate returns. This skewness is manifested in the pricing of currency options at sufficiently FOM strikes. For instance, Figure 1 plots the Black and Scholes (1973)-implied volatility against a measure of moneyness at a fixed maturity, illustrating the classic implied volatility skew, indicating that the average slope of the plot is positively related to the risk-neutral skewness of the currency return distribution.[3]

I build a framework in which I rationalize the link between the two, formally seemingly unrelated, markets of FOM foreign exchange options and standardized sovereign CDS contracts by synthe-

[2]For example, in the three months period preceding the widely anticipated UK credit rating downgrade on February 22, 2013, the spread on the 5-year UK government CDS increased from 30 to 50 basis points. During the same period, the British pound (GBP) depreciated by more than 5% against the US dollar. During the period, in derivatives markets, investors positioned against the GBP, with net speculator positions changing from about 30,000 contracts long to 30,000 contracts short. The implied volatilities of US dollar/GBP options surged, specifically, for put relative to call options, reflecting the market's perception of tail risks and increased cost of crash insurance. Notably, the downgrade was only one notch down from AAA; therefore, the UK was far from actually defaulting on its debt (Della Corte et al., 2021).

[3]Furthermore, similar to Barro and Liao's (2020) results for FOM corporate equity options, the elasticity of the implied volatility of FX put options with respect to a measure of moneyness (e.g., delta) is quite linear in the sufficiently FOM put options section (e.g., closer to 0 delta), as opposed to being strictly convex nearer to the at-the-money (ATM) section (closer to 50 delta).

Figure 1: Implied volatility against moneyness (delta).



Note: This figure displays the implied volatility of currency options on four G7 currencies versus the US dollar against a measure of moneyness (option's delta) on February 10, 2017 and February 10, 2020

sizing the preceding stylized facts and by imposing no-arbitrage conditions. The key sufficient condition for this link is that a currency crash occurs concurrently with a sovereign default, which empirically I cannot reject.[4] This implies that the foreign exchange rate is above a higher barrier H prior to default, but falls below a lower barrier $L < H$ at default and remains below L thereafter. The range $[H, L]$ defines an FX default (crash) corridor, which is assumed to coincide with a sovereign default.

When I test the link of the framework empirically, I find that a claim on a portfolio comprised of a spread between FOM FX options is equivalent to a claim on a pure CDS contract that pays off

[4]Regarding the marginal probability of a currency crash upon a default, it is somewhat reasonable to believe that changing credit conditions prior to default should have no effect on the probability of depreciation that is conditional on the occurrence of a default and it is supported by the numerous empirical studies including, for instance, Na et al. (2017) finds that sovereign defaults are followed by a one-time crash in the exchange rate. Reinhart (2002) documents that the historical probability of devaluation in the event of a sovereign default is sufficiently close to 1 (e.g., 0.84), while Du and Schreger (2015) and Lando and Nielsen (2018) find that this probability is relatively constant over time.

if an only if the sovereign defaults before the option expiry, i.e., FOM FX options can be used to insure against sovereign CDS credit risk and vice versa. The shorter the maturity, the closer the relationship is to one another. Furthermore, re-running the analysis on sub-samples over time reveals that this relationship is relatively constant post-2014. The claim on the portfolio comprised of FOM FX options is not only a bet on credit default risk but is also an implicit bet on higher order moments of the exchange rate distribution, hence the findings give evidence on the relationship between sovereign risk and those higher order moments. Thus, the positive relationship between the claim on the portfolio of the FOM FX options and the claim on the CDS implies that higher sovereign risk is associated with a higher cost of insuring against exchange rate skewness and kurtosis risk. I also show that this result has no reliance on delta and vega, however, it is determined by the asymmetry of the implied volatility smile, which reflects the skewness and kurtosis (the higher moments) of the exchange return distribution.[5]

Meanwhile, a puzzle emerges that, in terms of levels, the cost of a claim on the portfolio of FOM FX options is typically higher than the cost of a claim on a CDS contract. This cross-market deviation result is suggestive of some form of segmentation between the credit and FOM exchange rate options markets. As a result, even after accounting for liquidity and transaction costs, a 5-year trade between the two markets (cross-markets trade), on average, offers a 3.55% in profits per week and an annualized Sharpe ratio in excess of 7.2. In comparison, the classic momentum strategy has a Sharpe ratio of about 1.7 on average. The cross-markets trade is performed by purchasing a CDS and simultaneously selling a matched maturity FOM FX put spread struck within the FX default corridor. Even more remarkable is that the large cross-market trading profit occurs during times

[5] The trading strategy is similar to, for example, the skewness asset developed by Bali and Murray (2013) and the several higher moment swaps developed by Della Corte, et al.,(2021) and by Schneider and Trojani (2019a,b, 2020), but it is slightly easier to implement.

of tranquilly, while the segmentation between the two markets, and thus the opportunity to profit by performing the cross-market trade disappears during times of crisis, such as sovereign default. This is due to the evidence that during times of crisis, the correlation between the two markets becomes one since the two markets begin to start behaving as if they are one.

While this cross-market trade could be a viable profit opportunity for a small number of unconstrained investors, other limits to arbitrage that could prevent such potential trading profits are not ruled out for other investors. Balance-sheet and regulatory constraints are among these limits. They are similar to those documented in the literature on Covered Interest Rate Parity (CIP) violations and, due to their breadth, are left to be studied further in a separate study.

Another competing explanation is that the FOM FX options are pricing in a latent peso risk premia for a state of the world in which currency crashes occur but are not accompanied by sovereign defaults. This scenario is theoretically possible, but has almost never occurred, hence being a peso event, in developed countries such as the G7 ones studied here. Furthermore, because the trading profitability from cross-market deviations vanishes during times of crisis, this evidence lends less credence to this hypothesis. According to this hypothesis, the probability of a currency crash should increase during times of crisis, such as sovereign default, and thus the FOM FX options market should be priced even higher than the sovereign CDS market, contributing to a higher, rather than lower, market segmentation during times of crisis.

Interestingly, the empirical evidence suggests that these cross-market deviations (segmentations) are related to the quanto spread, which is the spread on the credit interest rates on LC debt versus FC otherwise equivalent debt. Based on the sample data in this paper, the quanto spread ranges between -74 and 24 basis points. Therefore, for instance, on the same 5-year cross-market trade, a one basis point less negative quanto spread corresponds to a 1.62% increase in the cross-market deviation, which is a greater potential profit opportunity when trading between the two markets.

I further find that the quanto spread, in turn, is strongly related to a quantitative measure I develop called "distance to crash", which is measured as the distance between the higher default barrier, H, and the spot exchange rate. The lower the distance, the higher the distress. The results indicate that lower distance to crash leads to more negative quanto spread discount.

The evidence of the aforementioned relationship between the distance to crash and the quanto spread is novel but it is theoretically relatable to the concept of loss uncertainty given default in traditional credit models such as Duffie and Singleton (1999). To use an analogy from their model, the quanto spread is related to the relative devaluation loss, i.e. the variation in the expected relative magnitude of currency crash drives the variation in the quanto spread.

Moreover, the distance to crash measure appears to be related to the carry trade as well. The higher the currency crash risk (lower distance to crash), the higher the carry trade risk premium. This is because the carry trade is associated with the higher moments of the exchange rate distribution, such as increased skewness and kurtosis, which are reflected in these measures.

Finally, while not explicitly postulated by the theory in the framework, I show empirically that, in a price discovery, the information flows from the sovereign credit market to the FOM FX options market. This finding opens up a new channel of price discovery in the market for exchange rate options.

The implications and contributions of the findings are several. First, they point to a novel way of quantifying the risk-neutral probability of a currency crash conditional on default from FOM options as well as disentangling it from the expected magnitude of the crash. Second, they shed light on a new approach to insuring sovereign credit risk through the use of FOM FX options. Third, they highlight a strong correlation between the risks of sovereign default and currency crashes, which investors should be aware of when managing portfolio concentration risks. Fourth, because there is suggestive evidence of segmentation between the two markets, these anomalies have broader market efficiency implications. Finally, they show how the relationship between the two markets affects the pricing of LC relative to FC sovereign debt via the quanto spread discount as well as the carry trade.

To the best of my knowledge, no prior research has explored the empirical relationship between FOM FX options, sovereign credit risk, quanto spread discounts, and carry trade. The findings have broader implications for global sovereigns seeking to optimize the cost of their borrowing currency mix, as well as international investors managing currency and sovereign debt risks.

2 Related Literature

The study is related to several literature streams. First, it is related to the classic literature establishing that foreign exchange markets are connected to sovereign credit markets by analyzing rare historical sovereign default events. Particularly, a default on sovereign debt has been historically associated with significant devaluations of the sovereign's currency (Reinhart 2002, Na et al. 2017). Several mechanisms contribute to this effect, such as, capital outflows during default (Fuentes and Saravia 2010), domestic economic slowdowns stemming from loss of private corporations' access to international capital markets (Arteta and Hale 2006), and contraction of domestic credit (Gennaioli et al. 2013). Currency depreciation and economic contractions can also precede and induce sovereign default.[6] I use this well-documented relationship in that currency deprecia-

[6]See Levy-Yeyati and Panizza (2006) for a discussion of the timing of output contractions and default.

tion and sovereign default often occur together as a fundamental building block in my no-arbitrage framework. In particular, I use the evidence of Reinhart (2002) that the historical probability of devaluation conditional upon a sovereign default is sufficiently close to 1 (e.g., 0.84) to support the framework assumption about the existence of an exchange rate default corridor, which the FX brakes by crash depreciating conditional upon a sovereign default.

Second, this paper is related to the asset pricing literature that documents a relationship between sovereign credit and FX options, arguing that investors are sensitive to the risk this relationship creates. For instance, by employing a model with joint currency return variance and sovereign default intensity, Carr and Wu (2007) document that, for Mexico and Brazil, sovereign CDS spreads covary with both the FX option-implied volatility and the slope of the implied volatility curve in moneyness. Hui and Fong (2015) identify a cointegration between the skewness of the FX rate distribution measured by FX risk reversals and the sovereign CDS spreads in a group "safe haven" currencies and the euro. Furthermore, in a manner similar to these studies, I investigate the information content of FX options, but of FOM options. I also agree with their evidence that the covariance between sovereign CDS spreads and FX option-implied volatility decreases with moneyness, i.e., is greater for FOM options. However, the primary goal of these studies is to document the relationship between the FX option and sovereign CDS markets. I empirically support this relationship, but I also go a step further by disciplining the relationship in a no-arbitrage model and identifying the distributional properties of the covariance between exchange rates and credit markets, as well as developing novel no-arbitrage conditions, implementable pricing, and tradeable strategies between the two markets.

My findings also complement the earlier work on properties of the variance and skewness in exchange rates (Bakshi 2008; Du 2013; Della Corte et al. 2016; Londono and Zhou 2017)) and on crash risk in currency markets (Brunnermeier et al. 2008; Chernov et al. 2018; Farhi et al., 2015; Farhi and Gabaix 2016; Hodrick et al., 2017). The link between sovereign risk, higher exchange rate moments, and currency crash risk suggested by my empirical results is also consistent with the literature on asset pricing implications of rare events for credit spreads and option prices recently surveyed by Tsai and Wachter (2015).

A third relevant research stream studies "quanto spreads", which are the price differences in the otherwise identical sovereign credit spreads that are denominated in different currencies. By analyzing the difference in premiums of the Euro-denominated and US dollar-denominated sovereign debt CDS contracts, Augustin et al. (2018) examine how investors price the interaction between exposure to the euro currency and to the sovereign debt default risk of Eurozone constituents. They find that investors are very sensitive and price the 1-week risk-adjusted probability of currency devaluation conditional on default at 0.75, which is much higher than suggested by the true historical probability. Du and Schreger (2015) similarly use quanto spreads on CDS contracts in emerging market economies and find that the risk-neutral market expectation of depreciation upon a default for Mexico and Brazil is approximately 0.36. They find that the quanto spreads are quite stable, implying a somewhat static view on currency depreciation conditional upon a default. Della Corte et al. (2021) generalize a model from Kremens and Martin (2019) to identify currency returns arising from sovereign credit crash risk and estimate implied LC devaluation probability conditional on default for the eurozone of about 0.25 on average. Their estimation implies more variance in the FX depreciation conditional on default than that of Du and Schreger (2015). Moreover, Pu and Zhang (2012) and Mano (2013) compare US dollar and euro denominated sovereign CDS spreads for Eurozone countries to investigate whether the differential (the quanto spread) conveys information for the euro currency, with Mano (2013) focussing on expected depreciations given the default of member countries.[7] A related dimension is whether the sovereign default has an immediate or long-term impact on the exchange rate. For instance, Na et al. (2017) argue that a default leads to an immediate one-off crash in the exchange rate, while Krugman (1979) argues that a default leads to a gradual long-term depreciation in the LC.

Lando and Nielsen (2018) make a distinction between two risk sources in the quanto spreads—an expected LC depreciation conditional on a sovereign default and a "distress premia" associated with uncertainty regarding the level of covariance between credit risk and exchange rates and their volatilities. They find that the distress premia is highly time-varying and has a small impact on the quanto spreads at shorter maturities. Della Corte et al. (2021) find that LC holders are rewarded with excess returns for holding high-sovereign risk currencies and that this excess is driven primarily by default expectations (rather than distress premia). I separate the quanto discount spread similarly, but focus and identify only the probability of depreciation conditional on default, represented by the tail of the exchange rate distribution, by directly observing the distribution of very FOM FX options. Complementing the above studies, I show that this probability is relatively constant and contributes significantly to the quanto spread at shorter to mid term maturities.

In other asset class markets, Carr and Wu (2011) find a similar a connection between corporate CDS contracts and FOM equity put options using a similar model. Barro and Liao (2020) establish the same relationship, but use it to build a FOM equity option pricing model. Both studies' models are based on the empirical feature that FOM put options price's (implied volatility) elasticity is

[7]See also Tse and Wald (2013), who find that using sovereign CDS spreads sheds some light on the forward premium puzzle but argue that CDS spreads have no explanatory power for carry trade returns.

linear with respect to its exercise price. This is because the payoff of the sufficiently FOM options is dependent on the dominating default intensity, rather than on any price process of the underlying option equity, and because once a credit default occurs, the payout is practically a fixed lump sum. I refer to these models' essential features when building and testing the no-arbitrage model; however, I apply them to the connection between the sovereign CDS contracts and FOM FX put options, which is a novel approach in the sovereign credit risk management literature.

Fourth, my research also informs related works on CDS premia sources, such as Longstaff et al. (2011), Ait-Sahalia et al. (2014), and Pan Singleton (2008), sovereign bonds market dynamics, such as Chaieb et al. (2020a) and Jean-Charles et al. (2015), international stochastic discount factors, such as Trojani et al. (2020), and as pioneered by Lustig and Verdelhan (2007) currency premia sources, such as the interest rate differential premium (Londono and Zhou, 2017, Sarno et al. 2012), quanto-implied risk premium (Kremens and Martin 2019), volatility risk premium (Della Corte et al. 2016; Marsh et al. 2020), liquidity premium (Chaieb et al. 2020b; Karnaukh et al. 2015; Mancini et al. 2013), portfolio-based currency factors (Lustig et al. 2011; Menkhoff et al. 2012; Gabaix and Maggiori 2015; Hassan and Mano 2019), and credit-implied risk premium (Della Corte et al. 2021).

3 Institutional Background

Given the peculiarities of the instruments considered in this study, I provide a brief overview of the CDS and FX options markets. A CDS is a form of debt insurance against the default of an underlying reference entity. If a credit event occurs, the buyer is reimbursed for the amount of the notional protected. Credit events in CDSs are defined by the International Swaps and Derivatives Association (ISDA) and include a variety of scenarios such as outright bankruptcy, debt restructuring, or deferred interest payments.

In the event of a credit event, an auction is held to determine the recovery rate based on a pool of bonds delivered into the auction. The recovery rate is the same for all CDS contracts based on a specific referenced sovereign, regardless of currency denomination. Once a default event has occurred, protection buyers are entitled to a settlement by physically delivering any of the specified deliverable obligations to settle the contract. According to the standardized ISDA terms, the deliverable bonds must meet a number of requirements. Payments must be made in one of the following currencies: euro (EUR), British pound (GBP), Japanese yen (JPY), Swiss franc (CHF), Canadian dollar (CAD), Australian dollar (AUD), or US dollar. This means that a holder of a CDS contract on the Australian sovereign denominated in US dollars can deliver Australian sovereign bonds denominated in AUD. The relevant exchange rates for delivering obligations in a different currency to the CDS contract are set at a mid-point rate one day before the auction at a predetermined time.

Regarding the FX options market, it has become market practice for international banks to use FX option designed hedges to risk manage their wrong-way sovereign CDS positions since the 2008 financial crisis. These wrong-way CDS exposures are sovereign CDS transactions entered into with counterparties who have a high correlation with the same sovereign CDS transaction's underlying. European banks, for example, were highly correlated with their domicile sovereign credit risk during the 2009-2010 European sovereign credit crisis. As a result, engaging in a sovereign CDS transaction with such a bank exposed international banks to significant wrong-way risk. When the European sovereign's credit rating deteriorated, the European bank was obligated to pay a negative mark-to-market under the CDS contract transaction. However, at the same time, its own credit quality deteriorated, making it less likely to honor its negative mark-to-market payment. As a result of a covariance with the deterioration of sovereign credit, the EUR currency depreciated. Consequently, in such cases, international banks started buying FOM FX put options to hedge their CDS transaction with a counterparty with a wrong-way credit exposure.

In terms of FX options market conventions, a stylized fact in the OTC market is that FX options are quoted based on their delta (δ) rather than their strike, as is the case in other options markets. This reflects the sticky delta rule, which states that if the related moneyness remains constant, implied volatilities do not vary from day to day. In other words, when the underlying exchange rate changes and the delta of an option changes, a different implied volatility must be plugged into the corresponding Black and Scholes (1973) formula. Moreover, the options are quoted in terms of Garman and Kohlhagen (1983)-implied volatilities on baskets of plain vanilla options, at fixed deltas and with constant maturities. For a given maturity, quotes are typically available for nine different option combinations: delta-neutral (0δ) straddle (V_{ATM}), 5δ, 10δ, 25δ, and 35δ risk-reversals (RR_{δ}), and 5δ, 10δ, 25δ, and 35δ butterfly spreads (B_{δ}).[8] The delta-neutral straddle is equivalent to buying a call and a put option with the same maturity and identical absolute deltas. The implied volatility of this strategy equals the ATM-implied volatility quoted in the market. In a risk reversal, the trader buys an out-of-the money (OTM) call and sells an OTM put with symmetric deltas. The butterfly spread combines a long strangle with a short delta-neutral straddle. The market practice is to calculate particular delta call (C)- or put (P)-implied volatility (V) from data on ATM-, straddles-, and butterfly-implied volatilities using the following formulas that I utilize in

[8] In line with market conventions, for instance, a 5δ call option has a delta of 0.05 and a 5δ put option has a delta equal to -0.05.

this study.

$$V_{C,\delta} = V_{ATM} + B_\delta + \frac{1}{2}RR_\delta, \qquad \text{for Calls} \tag{1}$$

$$V_{P,\delta} = V_{ATM} + B_\delta - \frac{1}{2}RR_\delta, \qquad \text{for Puts} \tag{2}$$

Finally, in terms of liquidity, sovereign CDS contracts are the most actively traded credit insurance contracts in the OTC market. Their bid-ask spreads in my sample average around 10% of their premium (summarized in Table A.1 in Chapter II Appendix A). Also, the FOM FX options I investigate are more actively traded than comparable FOM options in other asset classes, such as equities options, which have been extensively researched in the literature. The percentage quoted bid-ask spreads vary by currency pair, but for both ATM and sufficiently FOM FX options, they average between 7–10% of their premium. This may be perplexing given the much higher levels of activity in the ATM FX options markets; however, the FOM FX option prices provided by Bloomberg are for quotes with a notional value of $10 million. Furthermore, conversations with market participants indicate that depths of $20-30 million at the quote are typical for the G7 currencies I study, and that price improvement relative to Bloomberg quotes is common in the market.

4 Model

The model is developed around a no-arbitrage link between FOM FX options and sovereign CSD markets. It is based on models including those of Carr and Wu (2011) and Barro and Liao (2020), which establish a link between other asset-class markets, such as between equity options and corporate CDS markets. These studies also use the link to generate equity option pricing models.

4.1 Setup

To compare quantities between different levels and payoffs, I built the model around simple normalised Arrow-Debreu claims (ADCs) with a payoff of one unit across all asset classes (FX options or CDS). In essence, the model matches ADC contracts built from CDS prices with those built from FOM FX option prices. The key assumption that allows for a no-arbitrage link between the two is the existence of a default corridor $[H, L]$. The FX rate, S_t, remains above a higher barrier H prior to a sovereign default, but falls below a lower barrier $L < H$ after default and remains there afterwards. This results in a default corridor $[H, L]$ into which the spot FX rate can never enter prior to a default. Furthermore, the FX rate is expected to crash from a higher value just before a default to a lower value at a default. Because any ADC pays off one unit in the case of default, I am able to remain agnostic about the size of the FX crash upon default, so it is fixed at one unit for the time being.

To support the model assumption about the existence of an FX default corridor, and thus assume constant marginal density functions for the currency crash conditional on a default and the default conditional on a currency crush, I rely on a large body of empirical literature. As detailed earlier, for example, Reinhart (2002) documents that the historical probability of devaluation conditional on a sovereign default is sufficiently close to one (e.g., 0.84), and Augustin et al. (2018) find that investors are extremely sensitive to devaluation risk conditional on a default, pricing the 1-week risk-adjusted probability at 0.75. On a related note, Na et al. (2017) show that a sovereign default is related to a one-time crash jump in the exchange rate.

Given the existence of this FX default corridor, a spread between two co-terminal American FX put options struck within it can replicates a sovereign credit contract paying off if and when default occurs prior to or at the expiry of the American options. To build this replicated credit contract requires two American FX put options with the same maturity, T, but different strikes: $K_1 \in [K_2, L]$ and $K_2 \in [H, L]$. By purchasing a put option with strike K_1 and writing a put option with strike K_2, one creates a vertical spread position that costs $P_t(K_1, T) - P_t(K_2, T)$ to enter and pays $K_1 - K_2$ if and only if a default occurs. When the put spread price is normalized by the difference in the strike prices, such a position generates a synthetic standardized credit insurance contract, so called FX-based ADC, that pays one US dollar at default if the sovereign defaults prior to or at the expiry of the FX options and pays zero otherwise and costs:

$$D^{fx}(t, T) = \frac{P_t(K_1, T) - P_t(K_2, T)}{K_1 - K_2} \tag{3}$$

If the sovereign does not default before the FX options expire, the model assumes that S_t will remain above K_1, and thus neither put option will be exercised, as they have zero intrinsic value. If a default occurs prior to the expiration of the FX options and the FX rate falls below K_2, the FX rate is assumed to remain below K_2. As a result, the spread is worth its maximum possible value, $K_1 - K_2$, and exercising both options at the default time is optimal. Note that to obtain an FX-based ADC, the two traded options can be struck virtually anywhere within the default corridor, not just at the barriers. This is due to the fact that FOM option prices are linear with respect to their strikes anywhere within this corridor, so their slope is constant.

To generate an analogue normalization for a CDS contract denominated in US dollars, I build an ADC from a sovereign CDS spread that pays one US dollar at default if $\tau \leq T$ and zero otherwise. A CDS spread of any maturity can be used if the default arrival rate (λ) is assumed constant (flat term structure). Indeed, assuming a fixed and known sovereign bond recovery rate and deterministic interest rates (r), I derive the analytical value of an ADC from a single CDS spread price.[9] This CDS-based ADC's price is as follows:

$$D^{cds}(t,T) = E_t^Q[e^{-r\tau}1(\tau < T)] = \int_t^T \lambda e^{-(r+\lambda)s} ds = \lambda \frac{1 - e^{-(r+\lambda)(T-t)}}{r+\lambda} \tag{4}$$

In comparison, over the same time horizon, the risk-neutral default probability is:

$$RN^{cds}(t,T) = E_t^Q[1(\tau < T)] = \lambda e^{-(r+\lambda)s} ds = 1 - e^{-\lambda(T-t)} \tag{5}$$

which is the forward price of a claim that pays one US dollar at expiry if there is a prior default. Comparing the two expressions, the risk-neutral default probability is higher than the present value of the ADC.

In short, according to the model, as long as the FX default corridor exists and two traded put options are struck within it, the simple spreading strategy, FX-based ADC, replicates a standardized credit contract, CDS-based ADC, regardless of the details of the FX rate, interest rate, and default intensity dynamics prior to default.

4.2 No-arbitrage

Because the CDS-based ADC and the FX put option-based ADC have the same payoff, one US dollar, that is paid conditionally only upon default, no-arbitrage dictates that they should have the same price. According to the model, if the market prices of two FOM puts $P_t(K_2, T)$ and $P_t(K_1, T)$

[9] Chapter II Appendix B discusses the relationship between CDS contracts and ADCs in greater detail.

struck within the default corridor are available, one can infer the value of the CDS-based ADC from them:

$$D^{fx}(t,T) = \frac{P_t(K_2,T) - P_t(K_1,T)}{K_2 - K_1} = D^{cds}(t,T) \tag{6}$$

where cds and fx denote the information source as CDS-based and FX-based, respectively.

When using an FX put option-based ADC to replicate a CDS-based ADC, the model's intuition is that the FX rate underlying the FOM options' spread either spends time below the lower strike price or does not. Similarly, a CDS-based ADC either pays off one US dollar due to default or expires worthless.

The model assumes that in the event of a default, the FX rate crosses the default corridor located lower strike K_2 (which is allowed to be very close to the upper strike K_1 if necessary). However, in the event of a sovereign default, the FX rate could move in a variety of directions not just below the lower strike K_2. While the state space of outcomes is divided into two-by-two logical partitions, the matrix in Figure 2 shows that two of these four outcomes are quite unlikely.

The FX rate could fall below the FOM lower strike put without triggering a CDS default (partition 2). While this scenario is unlikely, it is theoretically possible if aggressive, unconventional, and unexpected monetary policy shifts, such as unconventional rate cuts in response to say high inflation, happen without being accompanied by deteriorating macroeconomic conditions reflected in the sovereign credit risk. Therefore, this scenario is theoretically possible, but has almost never occurred, hence it is a peso event, in developed countries such as the G7 ones studied here. Also, given that the model applies to sufficiently FOM struck FX options, it is improbable that the FX rate depreciates so aggressively beyond the sufficiently FOM strike K_2 solely as a result of aggres-

Figure 2: Matrix of outcomes

FX rate \ CDS	Default	NO Default
Braking $[K_1, K_2]$	1 **MOST LIKELY**	2 **POSSIBLE BUT UNLIKELY**
NOT braking $[K_1, K_2]$	3 **POSSIBLE BUT UNLIKELY**	4 **LIKELY BUT NO IMPACT ON THE STUDY**

This figure displays the 2×2 logical partitions of the state space of outcomes related to all possible events at the intersection between FX rate and CDS markets.

sive monetary policy shifts, rather than any accompanying deteriorating macroeconomic conditions motivating the monetary policy shifts in the first place, which also affect the sovereign creditworthiness.

Furthermore, while a default could occur if the FX rate is higher than the strike of the FOM higher put K_1 (partition 3), such a scenario is equally implausible. The assumption that default causes a sudden crash jump in the currency value from above K_1 to below K_2 can be justified by loss of optionality and is supported by numerous empirical studies, such as Na et al. (2017), who document that default causes an immediate one-time crash drop in the exchange rate, and Reinhart (2002), who document that the historical probability of devaluation conditional on a sovereign default is sufficiently close to one (0.84) and Augustin et al. (2018), who find that the 1-week risk-adjusted probability of currency devaluation upon default is 0.75.[10] As a result, the most plausible scenario supported by these numerous empirical studies is the one in which the LC crash depreciates in the event of a default (partition 1).

The simple framework of this paper is based on the plausibility of partition 1 and assumes that neither of the aforementioned unlikely scenario partitions can occur. This model should not be applied if there is reason to believe otherwise. This conjecture can be further loosen by assuming marginal probabilities of a currency crash upon default and of a default upon a currency crash of less than one, but the results will still require constant densities. The intuitive reasoning for a the earlier constant density over time, in a sense that changing credit conditions prior to default should have no effect on the probability of depreciation conditional on default over time is consistent with many of the aforementioned studies.

4.3 Empirical Implication for FX Option Pricing

An apparent model implication is that an American-style FX put option struck within the FX default corridor can be priced using credit market information. For instance, assuming deterministic interest rates and a constant default arrival rate, as well as that the FX only recovers to the present value of the lower barrier of the default corridor L, i.e., $R_{fx} = Le^{-r}(T-\tau)$, the value of an American put option exercised only upon a default is:

$$
\begin{aligned}
P_t(K,T) &= E_t^Q\left[e^{-r\tau}[K - R_{fx}]1(\tau \leq T)\right] = \int_t^T \lambda e^{-\lambda s} e^{-rs}[K - Be^{-r(T-s)}]ds \\
&= K\left[\lambda \frac{1-e^{(r+\lambda)(T-\tau)}}{r+\lambda}\right] - Le^{-rT}\left[1-e^{-\lambda(T-t)}\right] \qquad (7)
\end{aligned}
$$

[10] Other studies include Na et al. (2017), who find that the true historical probability of currency devaluation conditional on default is 48%, Du and Schreger (2016), who estimate the same but calibrated risk-neutral probability at 36%, and Della Corte et al. (2021), who estimate also the same risk-neutral probability at about about 25% but with much higher variance.

where $r(t,T)$ is a deterministic continuously compounded interest rate, $\lambda = z(t,T) \times 1/(1-R)$ is the constant default arrival rate (R is the fixed recovery rate and $z(t,T)$ is the spread price of a CDS). Equation (7) shows that the value of a sufficiently FOM American put struck within the default corridor depends only on the default risk of the sovereign, but not on the pre-default FX rate dynamics. In particular, conditional on a fixed default arrival rate, the FOM American put value does not depend on the FX rate level and, hence, exhibits zero delta. Similarly, the value also does not depend on the pre-default FX return volatility and, in this sense, exhibits zero vega. The FOM American put value does depend on the sovereign credit recovery level R; however, the value of a vertical spread of two American puts both struck within the default corridor does not. This value is purely proportional to the strike price difference. Given the validity of my assumptions, the proportionality coefficient represents the value of the ADC.

5 Data

5.1 Credit Default Swap Data

I obtain data from Markit on CDS premiums on sovereign bonds issued by G7 countries in LC and US dollars.[11] Markit offers daily closing quotes with a maturity of 5 years. On CDS contracts, I use the complete restructuring clause (”CR”), which allows the protection buyer to deliver bonds of any maturity (and currency denomination) into the CDS auction. Markit goes through a number of data cleaning procedures on the CDS data that they receive from their contributors, such as removing stale quotes and outliers, and they only report quotes if there are at least three quotes from different contributors. Prior to August 2010, Markit combined quotes from different cur-

[11] Japan, Switzerland, United Kingdom, and New Zealand CDS spreads in local currency, as well as the same but with Canada and Australia CDS spreads in US dollars.

rency denominations into a single quote. I begin the analysis on August 1, 2010, and the sample ends on May 20, 2021, to separate out contaminations from the impact of mixing the currency of denomination on the pricing of CDS contracts.

5.2 Currency Options Data

In order to pin down the risk-neutral distribution of the exchange rate volatility at the tail of the distribution, which is where the currency crash risk dominates, I collect data on sufficiently FOM currency options. ATM options required for the quanto discount analysis are also included. From August 1, 2010 to May 20, 2021, I collect European exchange rate options data from Bloomberg consisting of Garman and Kohlhagen (1983) implied volatilities of 5, 10, 15, 25, 35 and 50 delta straddles, risk reversals, and butterflies. The maturities are set at six months, one year, two years, and five years. I then apply the market convention formulas (1) and (2) to calculate the implied volatilities of the plain vanilla put and call options. I also obtain spot FX, forward FX, and money market interest rates (Overnight Swap Rates - OIS) in each currency needed corresponding to maturity length of each option.

Some observations on the dimensions of the data are in order. First, I concentrate on a cross-section of G7 currencies, despite the fact that options data for some emerging economies is available for at least part of the sample period, they are not very liquid. I should be cautious and point out that my findings may only be relevant for advanced economies with options traded in liquid markets. To put it another way, I am aware that my findings are not influenced by smaller countries with less liquid options markets.

Second, I compute the option premia in terms of prices in US dollars using the deltas and implied volatilities and inverting the Garman and Kohlhagen (1983) formula. Option payoffs are also expressed in US dollars for ease of comparison. Chapter II Appendix C contains more information on the calculation procedure. Please see also Della Corte et al. (2016) and Jurek (2014) for a more detailed explanation.

Third, currency exchange market conventions dictate that the exchange rate for most currencies is quoted in FC units (US dollars) per one unit of LC. When the quoted exchange rate falls, a put option pays out. In the case of USD-JPY, this is when the US dollar falls in value relative to the Japanese yen. However, for the Australian dollar, Euro and British pound the rate is quoted as the LC price of one unit of US dollar, and puts pay out when the US dollar appreciates relative to the LC. Because of these cross-currency differences, I use puts or calls depending on the convention, but I then standardized them all to puts by changing the convention so that the FX options pay when the US dollar appreciates. This is accomplished by standardizing the options' FX rate quoting convention to FC units (US dollars) per one unit of LC and reconfiguring option premiums and payoffs to be in US dollars across all options analyzed.

6 Empirical Strategy

I use the theoretical no-arbitrage model to rationalize the empirical findings that follow. As a recap, the way I build the model is around simple normalized Arrow-Debreu claims (ADCs) with a payoff of one unit across all asset classes to help me compare quantities between different levels and payoffs (FX options or CDS). One ADC is constructed from the price of a vertical spread of FX put options normalized by the difference in their strikes, while the other is constructed from a sovereign CDS. Because I normalize all payoffs to one unit, I conveniently avoid making assumptions about the size of the currency crash in the event of a default (only for the analysis preceding the one on the quanto). I connect the ADCs of the two markets by assuming that the LC crash devalues immediately after a sovereign default, braking below an exchange rate default corridor. Because of the presence of this default corridor, an FX-based ADC is effectively a synthetic credit insurance contract by no-arbitrage, paying one dollar if the sovereign defaults before or at the expiry of the FX rate options' spread and zero if the sovereign defaults after the expiry of the FX rate options' spread.

I measure the sovereign credit risk using sovereign CDS spreads, which represent timely market information and allow for a more accurate assessment of sovereign risk compared to, for instance, sovereign credit ratings or sovereign bond yield spreads (Duffie et al. 2003; Pan and Singleton 2008; Longstaff et al. 2011; Palladini and Portes 2011; Augustin 2018; Ang and Longstaff 2013; Klingler and Lando 2018).[12] Furthermore, I use prices of European put options on FX rates (in US dollars) to measure the tail risk of the exchange rate distribution because data on their implied volatility prices is easily accessible from Bloomberg and they are liquid. Because American put options can be exercised at the same time when the CDS defaults, the model warrants using them. Even though American puts are typically more expensive than European puts, because I am obtaining ADC prices through a put spread, this spread is relatively invariant to the style of the option used. As a result, using European rather than American puts has little effect on the results.

I create weekly pairs of ADC estimates for a sample of six countries from August 1, 2010 to May 20, 2021. The maturity of the option contracts selected ranges from 6 months to 5 years. For each pair, I compute one ADC value from the price of a FX FOM European put spread using Eq. (3), and another ADC value from a CDS spread on the sovereign bonds using Eq. (4) under the assumption

[12] An important advantage is that sovereign CDS markets are typically more liquid than corresponding bond markets. Other advantages of using CDS data, also discussed in the literature on corporate CDS, include the comparability of CDS spreads across reference entities because of standardized CDS contract specifications (in terms of maturities, cash flows, default definitions, etc.) as well as avoidance of bond-specific effects related to covenants, taxes, and liquidity.

of a fixed and known bond recovery of 40% and deterministic continuously compounded interest rate r being the OIS rate ($\lambda = z \times 1/(1 - R)$ is the constant default arrival rate where R is the fixed recovery rate and z is the CDS spread price in US dollars). A CDS spread of any maturity can be used since the default arrival rate is assumed constant (flat term structure). Because it is the most liquid, I use the 5-year benchmark CDS across the entire term structure.

The model assumes the existence of an FX default corridor $[L, H]$ through which the FX rate should cross at default. I do not know the location of this corridor ex-ante. Because American put prices are linear in the strike price within the default corridor, if I could observe American put prices across a continuum of strikes at the same maturity, this corridor would emerge. This linear relationship's slope equals the value of the FX-based ADC, which is constant. Hence, to obtain an FOM FX-based ADC, the two traded options can be struck virtually anywhere within the default corridor, not just at the barriers. Outside of the default corridor, the put price is typically considered as a strictly convex function of the strike price.

In practice, options are only listed at a limited number of strikes. Therefore, to detect the default corridor, additional assumptions must be made. I assume that in the event of a sovereign default, the LC depreciates in a crash way straight below the lowest point, i.e., $L < H$, with a constant fixed probability of one. One can loosen this conjecture by assuming a probability of currency crash upon a default of less than one, but the results will still require that this density be constant. The intuitive reasoning for a constant density over time, in a sense that changing credit conditions prior to default should have no effect on the probability of depreciation conditional on default over time is a reasonable assumption supported by numerous empirical studies. For example, Na et al. (2017) finds that sovereign defaults are followed by one-time crash in the exchange rate. Reinhart

(2002) documents that the historical probability of devaluation in the event of a sovereign default is sufficiently close to 1 (e.g., 0.84) and Augustin et al. (2018) find that the 1-week risk-adjusted probability of exchange devaluation in the event of a sovereign default is 0.75.[13] Furthermore, Du and Schreger (2015) and Lando and Nielsen (2018) find that this probability is relatively constant over time.

Because I do not know the barriers of the default corridor ex-ante, I choose the two lowest strike (i.e. lowest delta) options available in the Bloomberg data to ensure that the FOM put options are struck within the default corridor. These are the 5 and 10 delta options in the main analysis, as well as the 10 and 15 delta options in Chapter II Appendix A's robustness checks. After selecting the contracts and strikes, I divide the mid-price of the European put options spread $P_t(K_2, T) - P_t(K_1, T)$ by the difference in the strikes $K_1 - K_2$ to obtain the FX-based ADC price.

7 Results

7.1 Link between sovereign CDS and FOM FX options markets

The first testable hypothesis of the model is that the FX-based ADC contract replicates the CDS-based ADC contract in terms of returns (changes) and levels. To test the hypothesis, I focus on the spread of the FX-based ADCs derived from the farthest FOM strikes—10 minus 5 delta—versus the CDS-based ADCs. A visual examination of the cross-markets in Figure 3 indicates that two sets of ADCs are cross-sectionally linearly related. Table 1 also shows that the markets are strongly connected as maturity increases; for example, the 5-year maturity has a cross-market correlation of 0.41 on average.

[13] Other studies include Na et al. (2017) who find that the true historical probability of currency devaluation conditional on default is 0.48, Du and Schreger (2016) who estimate the same but calibrated risk-neutral probability at 0.36, while Della Corte et al. (2021) estimate also the same risk-neutral probability at 0.25 but with much higher variance.

Figure 3: Cross-sectional relationship between Arrow-Debreu claims (ADCs)

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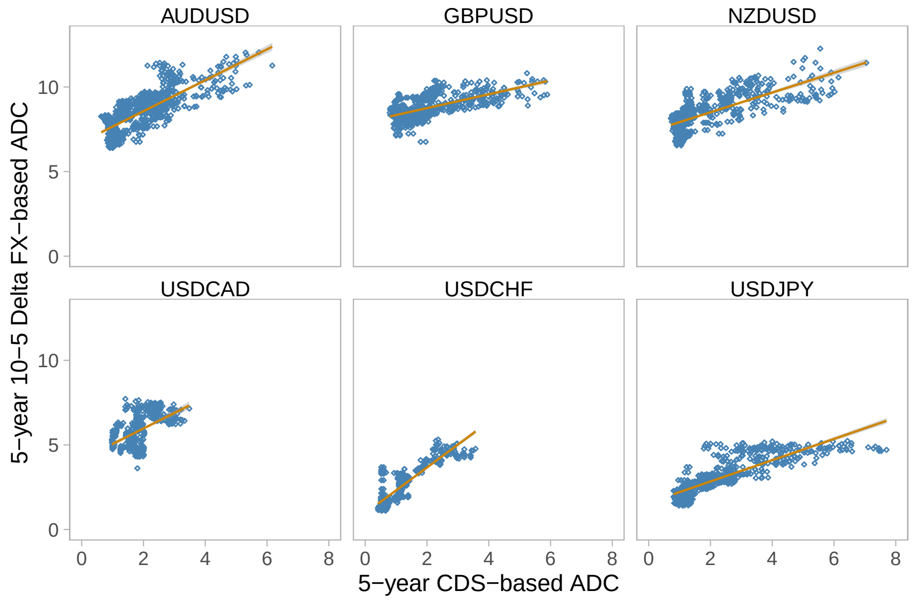


Note: Relationship between an ADC on a portfolio of 10-5 delta FX options and a coresponding ADC on a CDS. Prices are in cents (or %) per 1 US dollar payoff.

Table 1: Cross-sectional correlation between Arrow-Debreu claims (ADCs)

	6-month	1-year	2-year	5-year
ρ	0.21***	0.36***	0.43***	0.41***
t-stat	(13.69)	(25.71)	(29.03)	(29.15)
95% Confidence Interval	[0.18; 0.23]	[0.34; 0.39]	[0.40; 0.46]	[0.39; 0.43]

Note: The relationship is between an ADC on a portfolio of 10-5 delta FX options and a corresponding ADCs on a CDS for different maturities (weekly frequency). Null hypothesis: $\rho = 0$ and t-stats under the Null are in parenthesis. Significance: *** p<0.01, ** p<0.05, * p<0.1.

When I estimate a linear relationship between the two sets of ADC returns, as measured by their price changes, I get a slope estimate that is not statistically different from one. I obtain this by running regression Eq (8) separately for each maturity term. The results are summarized in Table 2 for the FX-based ADCs using 10-5 delta struck FOM put options' spread. The base results in Panel A include country and year fixed effects. To ensure that fixed effects are not driving my results, Panel B excludes fixed effects as a robustness check. Also as robustness check, Table A.2 in Chapter II Appendix A summarizes the results for the FX-based ADCs using the second furthest 15-10 delta struck FOM put options' spread and shows that, except for the 6-months tenor, the slope coefficients are statistically very different than one if the FX-based ADCs are built with insufficiently FOM options that are not struck within the FX default corridor.

$$\Delta D_{i,t}^{fx} = \alpha_i + \delta_y + \beta \Delta D_{i,t}^{cds} + \varepsilon_{i,t} \tag{8}$$

where α_i and δ_y are country and year fixed effects.

Table 2: Time series relationship between Arrow-Debreu claims (ADCs)

	6-month	1-year	2-year	5-year
Dep. Var.: Δ of claim on 10-5 delta FX puts		$\Delta D^{fx(10-5\delta)}$		
Panel A: Including country and year fixed effects				
ΔD^{cds} (β)	1.13	0.94	0.69	0.58**
t-stat	(0.39)	(-0.27)	(-1.64)	(-2.47)
Within Adj-R^2	0.04	0.05	0.07	0.03
Panel B: No fixed effects				
ΔD^{cds} (β)	0.93	0.75	0.62*	0.51**
t-stat	(-0.23)	(-1.19)	(-1.82)	(-2.54)
Within Adj-R^2	0.03	0.04	0.06	0.04
No. of Obs.	1,252	1,252	1,238	1,247

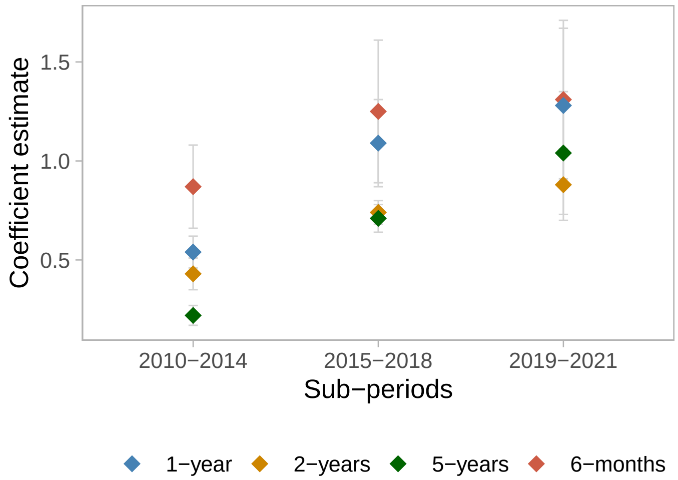
Note: This table presents panel regressions of weekly price changes of an ADC on a portfolio of 10-5 delta FX options ($\Delta D^{fx(10-5\delta)}$) on price changes of an ADC on a CDS (ΔD^{cds}) for different maturities testing the Null hypothesis of $\beta = 1$. Two-tailed t-stats are calculated under the Null hypothesis that $\beta = 1$ based on robust (two-way for the Panel B clustered by currency and time) standard errors and are shown in parenthesis. Significance: *** p<0.01, ** p<0.05, * p<0.1. ADF, PP, and KPSS tests indicated that the FX-based ADC series are non-stationary and integrated of order one, thus, for clean identification regressions are in first differenced variables.

The coefficient is statistically different from zero (at the 1% level) for all maturities for both the specification with fixed effects in Panel A and the one without fixed effects in Panel B. When fixed effects are excluded, the coefficients do not change materially, confirming that fixed effects do not drive the results. Given that the model assumes the probability of a currency crash conditional upon a sovereign default is one, the more appropriate null hypothesis is that the relationship between the two ADC returns is statistically equal to one. Looking at Panel A, based on the calculated t-statistics under this hypothesis shown in the parenthesis, I am unable to reject the null that the coefficient is different from one at the 1% significance level for all maturities except the 5-year maturity (which I reject but at the 5% significance level). The shorter the maturity, the closer the point estimate is to unity and the more statistically significant the link is.

Meanwhile, since FX-based ADCs, which are pure bets on credit default risk according to the model, are also implicit bets on higher order moments of the exchange rate distribution, the findings give evidence for the relationship between sovereign risk and those higher order moments. Thus, the positive regression coefficient obtained in Table 2 for each maturity length implies that higher sovereign risk is associated with a higher cost of insuring against exchange rate skewness and kurtosis risk, which is especially pronounced for shorter maturity terms. This result and trading strategy is similar to, for instance, the skewness asset developed by Bali and Murray (2013) and the several higher moment swaps developed by Della Corte, et al. (2021) and by Schneider and Trojani (2019a, b, 2020), but it is slightly simpler to implement.

Furthermore, re-running the regression on three sub-periods of the sample shows that the coefficient for each maturity is not completely constant over time. As shown in Figure 4, it increases, especially prior to 2014, but then remains relatively stable post-2014.

Figure 4: Time series relationship between Arrow-Debreu claims (ADCs) across sub-periods



Note: This figure presents the coefficients and standard error bands from panel regressions of price changes of an ADC on a portfolio of 10-5 delta FX options on price changes of an ADC on a CDS for different maturities during three different sub-periods.

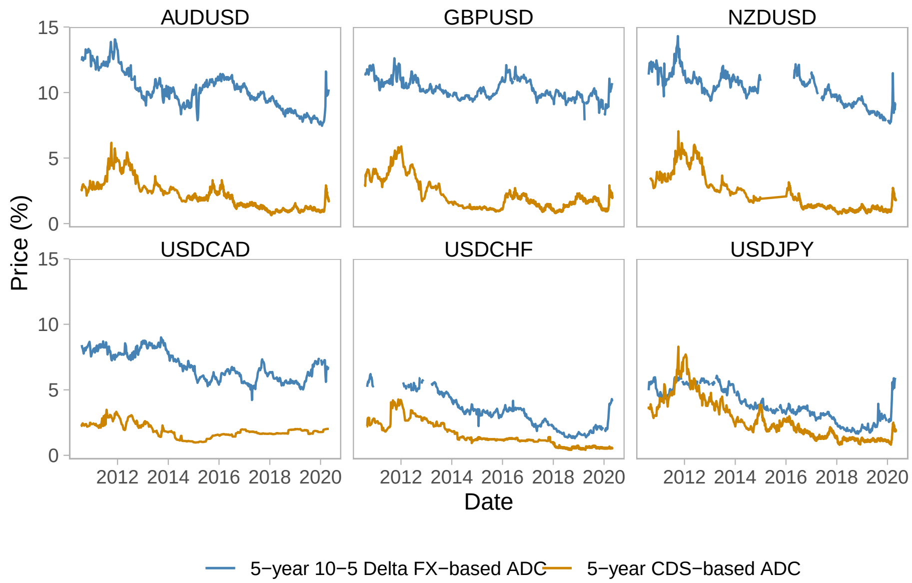
Overall, because FOM options identify the tail of the exchange rate distribution, the above findings cannot reject the key assumption of the framework in this paper, which is that the probability of currency crash depreciation in the event of a sovereign default is fairly constant and one, all the more so for shorter maturity terms and post-2014. This is not the case if the FX-based ADCs are built using insufficiently FOM options, as shown by the robustness check tests performed in Chapter II Appendix A.[14]

In terms of time series, a visual inspection of the two sets of ADC estimates reveals that they have similar statistical features in terms of changes (returns), as evidenced by the prior regression results, but not in terms of magnitudes of levels. For each country, Figure 5 plots the price of the 5-year 10-5 delta FX-based ADC versus the price of the CDS-based ADC. The plot shows rela-

[14]This could happen if the insufficiently FOM put options are struck slightly above the FX rate default corridor, which would violate the model's assumption, or if the actual risk-neutral probability of an FX crash jump conditional on a default is less than one. In the latter case, the results and conclusions are not materially altered as long as this relationship remains constant over time, i.e., as long as the density function of the currency crash jump upon a default remains constant.

tively large differences in the magnitudes between the two series. This evidence suggests that the hypothesis on the equivalency is partially supported; specifically, it is supported when the returns of the ADCs are examined but not when their levels are examined.

Figure 5: Time series properties of price levels of Arrow-Debreu claims (ADCs)



Note: This figure presents the time-series properties of price levels of an ADC on a portfolio of 10-5 delta FX options vs. a corresponding ADC on a CDS. Prices are in cents (or %) per 1 US dollar payoff.

Moreover, Table 3 summarizes the data from Figure 5 for all six countries for the 5-year maturity length for the full sample. As shown in Figure 5, the two sets of ADC prices co-move in the same direction over time. However, because the FOM FX puts are more expensive than the CDSs, the FX-based ADCs are frequently (by orders of magnitude) more expensive than CDS-based ADCs. When combined with the prior evidence suggesting that the returns of the two ADCs are co-moving one-to-one, this result suggests that crossing the two markets could result in a deviation offering a profit opportunity because it allows one to pay a lower price for asset returns that are co-moving one-to-one with the returns of a more expensive asset. This strategy could result in a potential weekly profit of 4.4%, as shown in Table 3 in the difference row. For the time being, this figure does not include liquidity and transaction costs.

Table 3: Summary statistics for 5-year ADCs

	Mean	Median	Min	Max	Std	N
All Countries						
$D^{fx(10-5\delta)}$	6.7	7.3	1.1	13	3.3	1247
D^{cds}	2.5	2	0.6	11	1.4	5336
Difference ($\mathcal{R}$)	4.4	5.9	-5.4	10	3	1236
AUDUSD						
$D^{fx(10-5\delta)}$	8.5	7.8	7	13	1.7	313
D^{cds}	2.6	2.4	0.8	8.2	1.3	790
Difference ($\mathcal{R}$)	6.7	6.3	5.5	10	1	313
GBPUSD						
$D^{fx(10-5\delta)}$	11	11	11	11	0.2	142
D^{cds}	2.5	2.2	1.1	7.9	1.3	963
Difference ($\mathcal{R}$)	6.3	6.1	5.3	7.2	0.6	142
NZDUSD						
$D^{fx(10-5\delta)}$	12	12	11	13	0.3	167
D^{cds}	2.4	1.7	1	9.4	1.5	928
Difference ($\mathcal{R}$)	7.7	7.6	6.9	8.5	0.4	160
USDCAD						
$D^{fx(10-5\delta)}$	5.5	5.4	4.3	7.4	0.9	293
D^{cds}	2.5	2.4	1.3	4.6	0.7	489
Difference ($\mathcal{R}$)	2.9	3.1	1.6	4.4	0.8	293
USDCHF						
$D^{fx(10-5\delta)}$	4.5	4.5	4.1	4.9	0.3	114
D^{cds}	1.8	1.6	0.6	5.7	1.1	784
Difference ($\mathcal{R}$)	1	0.9	0.5	1.9	0.5	114
USDJPY						
$D^{fx(10-5\delta)}$	2.6	1.5	1.1	4.6	1.5	218
D^{cds}	2.8	2.4	1.1	11	1.6	1382
Difference ($\mathcal{R}$)	-0.7	-0.4	-5.4	0.7	1.2	215

Note: This table presents the summary statistics for weekly price levels of a 5-year ADC on a portfolio of 10-5 delta FX options ($D^{fx(10-5\delta)}$) and a corersponding ADC on a CDS (D^{cds}) as well as their cross-market deviation ($\mathcal{R}$). Prices are in cents (or %) per 1 US dollar payoff.

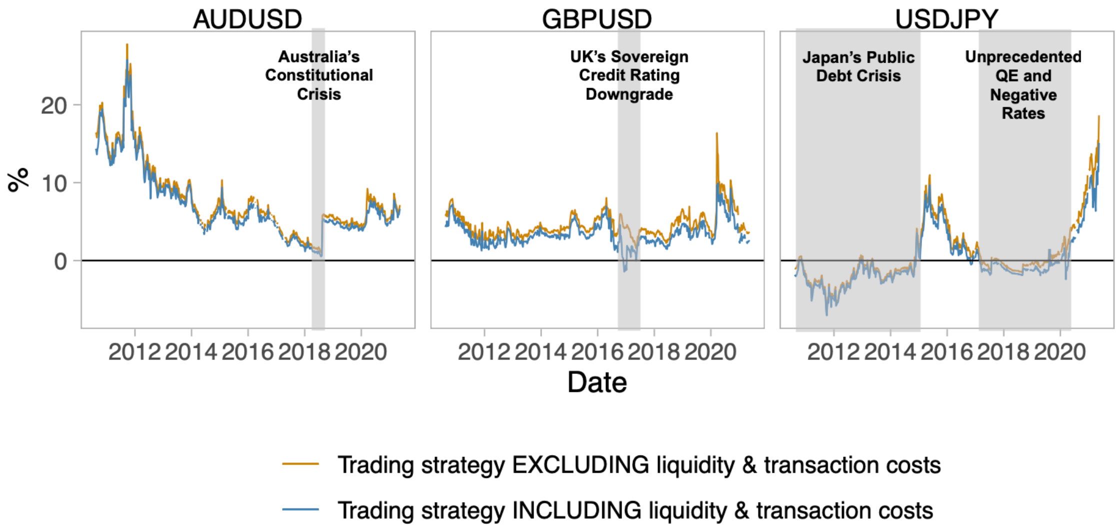
To investigate further, I devise a cross-market trading strategy to exploit this potential profit opportunity, but this time I account for liquidity and transaction costs. Because Markit data on CDS only includes mid prices, I use data on CDS bid and ask prices from Bloomberg instead for this analysis. Furthermore, Bloomberg only provides bid and ask prices for CDS premiums with a 5-year maturity and for Japan, Australia, and United Kingdom, limiting the scope of the analysis to those three countries.

Because the 5 and 10 delta FOM FX puts are more expensive than the CDSs, I make a zero-cost cross-market trade by selling a 10-5 delta FX put options' spread and buying a CDS. To match the payoff I will receive by selling the 10-5 delta FX put options' spread to the one I will have to pay under the CDS, I weight my investment in the 10-5 delta FX put options' spread by the inverse of the difference in the FX put options' strikes (exactly to obtain the FX-based ADC). As a result, the weight in the investment in the 10-5 delta FOM FX put options spread is negative $w^{fx} = 1/(K_{10\delta} – K_{5\delta})$ since shorting and in the CDS is positive $w^{cds} = 1$ since going long. Furthermore, because the FX option premium is upfront, I calculate the CDS spread in an upfront premium format (the CDS-based ADC) to make the two upfront premiums comparable.

Then, once a week, I do the following: (1) Sell a 10-5 delta FOM FX option spread with a weight of w^{fx} by selling a 10-delta put option ($P_t^{10\delta}$) at the bid price and buying a 5-delta put option ($P_t^{5\delta}$) at the ask price; and (2) buy a CDS, (D_t^{cds}), with a weight of $w^{cds} = 1$ at the ask premium. Because of the weights, each leg pays exactly one US dollar, making the investments comparable.

$$\mathcal{R}_t = w_t^{fx}(P_t^{10\delta} - P_t^{5\delta}) - w_t^{cds} D_t^{cds} \tag{9}$$

Figure 6: Select countries: Profitability of cross-market trading strategy



Note: This figure compares the potential weekly profitability of a cross-market trading strategy with 5-year ADCs that includes liquidity (bid-ask) and transaction costs to one that does not.

As shown in Table 4 and Figure 6, by excluding liquidity and transaction costs, on average, a cross-market trading strategy yields 4.46% in profits per week and an annualized Sharpe ratio of 8.7, which is consistent with the earlier result and confirmed by this data from Bloomberg. When liquidity and transaction costs from bid-ask crossings are factored in, this strategy yields a slightly lower but still solid 3.55% in profits per week and annualized Sharpe ratio of 7.2.[15]

Table 4: All countries: Profitability of cross-market trading strategy

	Annualized-SR	Mean	Median	Min	Max	Std	N
$\mathcal{R}_t$– *Exc. liq. & trans. costs*	8.7	4.5	4.2	-6.7	28	3.7	1655
$\mathcal{R}_t$– *Inc. liq. $ trans. costs*	7.2	3.6	3.2	-7.1	26	3.5	1655

Note: This table compares the expected profitability of a weekly cross-market trading strategy on the 5-year maturity tenor ADCs for all countries.Sharpe ratio is annualized. Except Sharpe ratio, prices are in cents (or %) per 1 US dollar payoff per week.

[15]The annualized Sharpe ratio is calculated as $SR = \frac{\bar{\mathcal{R}}_t - R_t^f}{SD(\mathcal{R}_t)} \times \sqrt{52}$

An interesting observation is that during times of crisis, such as Japan's public debt crisis in 2012, the UK's sovereign credit rating in 2012, or Australia's constitutional crisis in 2017-18, the cross-market market deviation (profit opportunity) disappears (or even reverses slightly for Japan).

7.2 What influences the cross-market deviations?

When the prices of the two market ADCs—CDS vs. FOM FX options—diverge (as previously shown in Table 3), allowing for potential cross-market profits, it is natural to wonder why. The evidence presented above points to market segmentation between the FOM FX options and sovereign CDS markets. In each of the two markets, different types of investors may be pricing the same risk differently. Indeed, in practice, investors in the FX options market (e.g., think of an FX trading desk in an investment bank) rarely have the mandate to participate in or exchange market information with investors who trade sovereign CDS, who frequently do not understand or trade FX option instruments (e.g., think of a sovereign credit trading desk in an investment bank). Thus, despite the fact that these two asset classes effectively insure against the same risk, different types of investors simply price them differently, resulting in a cross-market deviation. However, to further support this conclusion, we must rule out alternative explanations.

One alternative explanation for the cross-market deviation is that the FOM FX options are pricing in auxiliary peso risk premia for currency crashes that are not associated with a sovereign credit deterioration or default. This would make FOM option premiums more expensive than CDS premiums because they insure an additional currency crash risk that could occur in the absence of a sovereign deterioration or default. Such a scenario is theoretically possible but practically implausible, especially in market-based and developed countries like the ones studied here, because it almost never happened, so it is a peso event. This is because such a scenario would necessitate the country to run an easing monetary policy in times of high inflation while having no effect on the sovereign's borrowing capacity or credit risk. To the best of my knowledge, no theoretical macroeconomic model has been developed in the literature that predicts or rationalizes such an outcome.

Additionally, because profitability from cross-market deviations disappears during times of crisis, this evidence is less likely to support the aforementioned peso risk premia scenario because the probability of a currency crash, whether in the absence or presence of sovereign credit deterioration, should not decrease during times of crisis, but rather increase. Instead, as mentioned, based on institutional practice, a more plausible explanation is that the two markets are segmented in times of tranquility because the marginal investors in each market are experts who only trade their own asset class. However, in times of crisis, the marginal investors become so-called "hedgers." They are multi-asset risk hedging investors (think insurance companies or global investment banks' CVA desks, for example) who hedge their overall tail risk exposure during times of crisis. To do so, they use any of the two market instruments, FOM FX options or CDSs, to effectively hedge tail risk, causing prices to converge between the markets.[16]

Nevertheless, the potentially profitable trade stemming from the cross-market deviation may be feasible for a small number of unconstrained investors, however, there may be frictions and limits to arbitrage at work for many other constrained investors. These limits include institutional frictions similar to those documented in the CIP parity literature, such as balance sheet capital constraints and regulation, which are left as subject of future research.

Also, as noted by Goyal and Saretto (2009) and Murray (2013), the short leg of the FX options'

[16]These investors do not participate in both markets to hedge in times of tranquility because they are not concerned with tail risk at that time, but instead only enter whichever market is cheaper to hedge in times of crisis.

put spread may require investors to meet margin requirements in excess of the options' fair value. These margin requirements can be expensive. Margining and collateral have entered the FX options markets, and such changes have a negative impact on prices. Because the same margining conditions affect sovereign CDS prices similarly, such margining adjustments are unlikely to result in significant price differences between FX options and CDS derivatives that would materially affect the results presented above.

Moreover, I examine other factors at work that can be formally tested for. For example, the cross-market deviations are not fully explained by contemporaneous variables commonly used in the literature to explain fluctuations in FX option values. In contrast, the quanto, interestingly, helps in explaining them. The quanto spread is defined as the difference between sovereign credit spreads denominated in LC and FC in the traditional literature(Pu and Zhang 2012; Mano 2013; Augustin et al. 2018; Lando and Nielsen 2018; Della Corte et al. 2021).

To be consistent with the normalization used in this paper, I normalize the quanto spread and define it as the difference between the CDS-based ADC denominated in LC, (i), and the same but denominated in FC, (\$), further referred as the "quanto discount price" and calculated as in Eq (10). While both claims have a single unit payoff and the same recovery rate in the event of a sovereign default and LC devaluation, their payoffs in US dollars differ because one is paid in LC and the other in FC (US dollars). As a result, the crash size is no longer fixed at one unit. The quanto discount price is, in effect, the present value of the quanto spread as stated in the traditional literature, but it is expressed as a premium upfront per unit of payoff in each currency.

$$\boldsymbol{Q}\,(t,T) = D^{i,cds}(t,T) - D^{\$,cds}(t,T) \tag{10}$$

Furthermore, as in the previous analysis in Table 3, I calculate the cross-market deviation as the difference between the FOM FX-based and CDS-based ADCs denominated in US dollars. It is calculated using Eq (11) which is, in essence, the formal version of Eq (9) earlier.

$$\mathcal{R}(t,T) = D^{fx(10-5\Delta)}(t,T) - D^{\$,cds}(t,T) \tag{11}$$

While Eq (12) outlines the regression, Table 5 summarizes the results of regressing changes in the cross-market deviation using 10-5 delta struck FOM put options' spread on changes in common variables used in the literature as well as changes in the quanto discount price for each maturity (For robustness checks, Table A.3 in Chapter II Appendix A summarizes the same results but with a cross-market deviation using 15-10 delta struck FOM put options' spread).

$$\begin{aligned}\Delta\mathcal{R}_{i,t} = {} & \alpha_i + \theta_y + \psi\Delta Q_{i,t} + \delta\Delta S^{spot}_{i,t} + \upsilon\Delta IV^{ATM}_{i,t} + \rho_1\Delta OIS^{\$}_{t} \\ & + \rho_2\Delta OIS^{i}_{i,t} + \gamma\Delta Basis^{xccy}_{i,t} + \varepsilon_{i,t}\end{aligned} \tag{12}$$

where α_i and θ_y are country and year fixed effects, Q is the quanto discount calculated using Eq (10), S^{spot} is the spot exchange rate expressed as FC units (US dollars) per one unit of LC, IV^{ATM} is the ATM implied option volatility, $OIS^{\$}$ is the US dollar OIS interest rate, OIS^{i} is the LC OIS interest rate, and $Basis^{xccy}$ is the cross currency swap basis.

Except for the 6-month maturity for the implied volatility, it is clear that the spot exchange rate (delta) and implied volatility (vega) have no effect on the cross-market deviation changes. This

Table 5: Regressions on sources of cross-market deviations.

	6-month	1-year	2-year	5-year
$\mathcal{R}$ uses 10-5 delta FX puts	$\Delta\mathcal{R}_{i,t} = \Delta(D_{i,t}^{fx(10-5\Delta)} - D_{i,t}^{cds})$			
$\Delta Q_{i,t}^{(D^{i,cds}-D^{usd,cds})}$ (ψ)	1.62*	1.28**	1.27***	0.72**
	(0.85)	(0.64)	(0.35)	(0.31)
$\Delta FX_{i,t}^{spot}$ (δ)	-0.02	0.00	-0.02	0.01
	(0.01)	(0.01)	(0.01)	(0.03)
$\Delta IV_{i,t}^{ATM}$ (υ)	0.01***	0.00	0.01	0.01
	(0.00)	(0.00)	(0.01)	(0.02)
$\Delta US_{i,t}^{OIS}$ (ρ_1)	-0.02**	-0.01***	-0.00*	-0.01*
	(0.01)	(0.00)	(0.00)	(0.00)
$\Delta Local_{i,t}^{OIS}$ (ρ_2)	0.04**	0.02***	0.00	0.01
	(0.02)	(0.00)	(0.00)	(0.01)
$\Delta Basis_{i,t}^{xccy}$ (γ)	0.00	0.00	0.00**	0.00**
	(0.00)	(0.00)	(0.00)	(0.00)
Within Adj-R^2	0.35	0.12	0.28	0.19
No. of Obs.	1,252	1,252	1,238	1,247

Note: This table presents panel regressions of weekly changes in the cross-market deviations ($\Delta\mathcal{R}$) using a portfolio of 10-5 delta FX options on changes in the quanto spread (ΔQ) and other variables. The null hypothesis is that each slope coefficient is equal to zero. Significance: *** p<0.01, ** p<0.05, * p<0.1. Currency and year fixed effects are included and robust, two-way clustered standard errors by currency and time are shown in the parenthesis.

lack of reliance on delta and vega suggests that the model's assumption of the existence of the FX default corridor (zero-delta and zero-vega) is not likely violated. In other words, the result gives credence that the FX put options chosen to build the 5 and 10 delta FX-based ADCs are struck within the default corridor and not outside of it. Cross-currency swap prices and interest rates have a statistically significant impact on shorter maturities, but due to their economically insignificant magnitudes, this dependency has no material impact on the conclusions.

According to the model, if CDSs denominated in US dollars capture all credit risk information and the model assumptions are met, including that the selected FX options in the ACDs are being struck exactly within the default corridor, there should be no cross-market deviations, let alone variation; however, the empirical evidence suggests otherwise. As a result, CDSs denominated in

US dollars either do not summarize all credit risk information or other non-US dollar CDS-related factors account for the variation in the cross-market deviations. The evidence indicates that one of these factors is the quanto discount price.

In particular, the results in Table 5 show a statistically significant relationship between the variation in the cross-market deviation and the variation in the quanto discount price. This link is also economically meaningful. Depending on whether the maturities are six months or five years, a one-basis-point increase in the quanto discount price corresponds to a 0.72-1.62% widening in the cross-market deviation. This means that the narrower the quanto discount (e.g., closer to 0), the greater the potential cross-market profit opportunity.

One could argue that the cross-market deviation is being measured imprecisely, resulting in the aforementioned link. This could occur if the FX-based ADCs used to calculate the cross deviation were built from FOM put options that are not exactly struck within the FX default corridor. The option market's residual implied FX rate risk will then be reflected in the FX-based ADC prices, resulting in non-US dollar CDS-driven cross-market deviation. However, the regression results indicating that the cross-market deviation is unrelated to delta or vega do not support the notion that the model assumptions are likely violated. As a result, the connection between FOM cross-market deviations and quanto discount appears plausible.

7.3 What explains the Quanto?

Given that the quanto explains a sizable portion of cross-market deviations, a natural subtle question is what explains the quanto., i.e., the pricing of LC-denominated credit via a quanto discount to US-denominated credit. Table 6 presents the basic statistics of sovereign CDS premiums denominated in LC and US dollars, as well as their difference, the quanto spread, for four of the G7 countries. In what follows, I analyze the 5-year benchmark maturity due to adequate liquidity.

The US dollar CDS premium is noticeably higher than the corresponding LC CDS premium for all sovereigns. Intuitively, this is logical because a positive correlation between credit default and exchange rate depreciation means that, in the event of a default, the LC will likely depreciate, and thus the LC CDS insurance contract will pay a lower payoff when converted in terms of FC; thus, it is cheaper than the FC CDS insurance premium. As a result, the quanto spread is predominantly negative and sizable, averaging -9.2 basis points but ranging from -74 to 24 basis points across the countries studied. It is worth noting that the average FC debt credit spread for these so-called ”safe heaven” sovereigns is 32 basis points, thus the average quanto spread represents about one-third of their borrowing spread cost.

I postulate that three factors influence the quanto price: (1) the currency's spot exchange rate distance to a crash; (2) the US dollar CDS risk (“default intensity”); and (3) the expected change in the exchange rate implied by the UIP (assuming the UIP holds)[17]; So far, the last two factors are well documented in empirical literature (Du and Schreger (2015), Lando and Nielsen (2018), Kremens and Martin 2019). This study contributes the first factor.

If currency crashes occur concurrently with a sovereign defaults, the quanto discount price should naturally be related to the distance to currency crash (further referred to as ”distance to crash”) and default intensity. The higher the FX tail risk insurance cost (skewness and kurtosis), the higher is the sovereign credit insurance cost. The distance to crash measure reflects primarily the tail of the exchange rate distribution (skewness and kurtosis). I measure this currency crash tail distress risk by the proximity of the higher barrier of the FX default corridor, H_t, to the spot exchange

[17]However, because the UIP forecast is well known to perform poorly in practice, I do not expect the quanto to be significantly related to the UIP.

Table 6: Summary stats for CDS spreads in local currency vs. US dollars and their quanto spread.

	Mean	Median	Min	Max	Std	N
All Countries						
US dollar CDS	32	26	7	160	19	5336
LC CDS	21	17	7	88	13	3250
Quanto spread (Q)	-9.2	-8.5	-74	24	9.4	3244
GBPUSD						
US dollar CDS	32	27	13	100	17	963
LC CDS	21	16	7.8	85	15	937
Quanto spread (Q)	-10	-9.6	-36	3.5	5.8	937
NZDUSD						
US dollar CDS	30	21	12	120	20	928
LC CDS	19	17	7.9	57	8.2	484
Quanto spread (Q)	-0.6	0	-9	3.4	2.5	478
USDCHF						
US dollar CDS	23	20	7	72	14	784
LC CDS	19	17	7	68	14	481
Quanto spread (Q)	-0.2	0	-8.4	24	2.2	481
USDJPY						
US dollar CDS	39	33	14	160	22	1382
LC CDS	23	19	8.6	88	13	1336
Quanto spread (Q)	-15	-12	-74	-3.7	9.9	1336

Note: This table presents summary statistics for weekly 5-year CDS spreads denominated in local currency (LC) vs. foreign currency (US dollar) as well as their difference – the quanto spread (Q)CDS spreads are in basis points. The quanto spread is calculated as the difference between the LC and US dollar denominated CDS spreads.

rate, S_t which is measured by taking the ratio H_t/S_t (denoted as $\mathcal{DC}$). I chose the 10δ strike as the FX default corridor higher barrier based on the results from the first hypothesis. Therefore, the hypothesis here is that the closer the distance (the higher the ratio) to currency crash barrier, the closer the distance to a sovereign default and the higher the distress resulting in more negative quanto discount price.

To put this hypothesis to the test, I estimate Eq (13) by regressing changes in the quanto discount price on changes in the the distance to crash measure, the changes in the default intensity, the changes in the log UIP, and the changes in other common variables used in the literature.

$$\Delta Q_{i,t} = \alpha_i + \theta_y + \psi \Delta \mathcal{DC}_{i,t} + \xi \Delta D^{cds}_{i,t} + \omega \Delta s^{UIP}_{i,t} + \delta \Delta S^{spot}_{i,t} + \upsilon \Delta IV^{ATM}_{i,t}$$

$$+ \rho_1 \Delta OIS^{\$}_t + \rho_2 \Delta OIS^{i}_{i,t} + \gamma \Delta Basis^{xccy}_{i,t} + \varepsilon_{i,t} \tag{13}$$

where α_i and θ_y are country and year fixed effects. Q is the quanto discount calculated using Eq (11), $\mathcal{DC}$ is the distance to crash measure calculated as the ratio of the FX put option strike (higher barrier) to the spot exchange rate, D^{cds} is the US Dollar CDS-based ADC, and (Δs^{UIP}) is the changes in the log UIP expected exchange rate. Moreover, S^{spot} is the spot exchange rate expressed as FC units (US dollars) per one unit of LC, IV^{ATM} is the ATM implied option volatility, $OIS^{\$}$ is the US dollar OIS interest rate, OIS^{i} is the LC OIS interest rate, and $Basis^{xccy}$ is the cross currency swap basis.

The regression results are summarized in Table 7. The distance to crash measure is statistically significant at the 1% level and economically meaningful even after controlling for the default intensity (the US dollar CDS-based ADC), which is also significant, and the UIP implied expected change in exchange rate, which is not significant in column (3), as well as other controls in column (4). A 1% decrease in the distance between the currency crash barrier and the spot exchange rate (increase in the crash barrier to spot exchange rate ratio $\mathcal{DC}$ ratio) corresponds to a 0.21% more negative quanto discount price. Furthermore, a 1% increase in the level of US dollar CDS-based ADC corresponds to a 0.41% more negative, i.e., higher quanto discount.

This result suggests that crash risk is a significant input into the quanto discount price or, more specifically, the relative price of the LC-denominated sovereign credit. Although this finding is empirically novel, it is theoretically perfectly relatable and can be rationalized with the concept

Table 7: Regressions on quanto discount price.

	(1)	(2)	(3)	(4)
		$\Delta Q_{i,t}^{(D^{i,cds}-D^{usd,cds})}$		
$\Delta\mathcal{DC}_{i,t}$ (ψ)	0.15***	0.14***	0.14***	0.21***
	(0.05)	(0.05)	(0.05)	(0.07)
$\Delta D_{i,t}^{usd,cds}$ (ξ)		-0.38***	-0.38***	-0.41***
		(0.11)	(0.11)	(0.12)
$\Delta s_{i,t}^{UIP}$ (ω)			0.00	0.00
		.	(0.91)	(0.57)
$\Delta FX_{i,t}^{spot}$ (δ)				0.00
				(0.22)
$\Delta IV_{i,t}^{ATM}$ (υ)				0.01
				(0.09)
$\Delta US_{i,t}^{OIS}$ (ρ_1)				0.00
				(0.76)
$\Delta Local_{i,t}^{OIS}$ (ρ_2)				-0.00
				(0.32)
$\Delta Basis_{i,t}^{xccy}$ (γ)				0.01
				(0.25)
Within Adj-R^2	0.11	0.13	0.13	0.16
No. of Obs.	3,122	3,122	3,122	2,856

Note: This table presents panel regressions of weekly changes in the quanto discount price (ΔQ) on changes in the distance to crash ($\Delta\mathcal{DC}$) and other variables. The null hypothesis is that each slope coefficient is equal to zero. Significance: *** p<0.01, ** p<0.05, * p<0.1. Currency and year fixed effects are included and robust, two-way clustered standard errors by currency and time are shown in the parenthesis.

of loss uncertainty given default in traditional credit models such as Duffie and Singleton (1999). Using an analogy from their model, the quanto spread is related to the relative devaluation loss, i.e., the variation in the expected currency crash magnitude drives the variation in the quanto spread.

7.4 Where does price discovery originate from?

Finally, while not theoretically implied by the model, it is worth asking and hypothesizing that the information flows from the CDS market to the FOM FX options market during price discovery. To test the hypothesis, I use the generalized method of moments (GMM) to estimate the Panel Vector Autoregressive (PVAR) regression with fixed effects in Eq. (18) as in Fertsl and Sigmund (2021) (based on Hansen, 1982; Holtz-Eakin et al., 1988). Table 8 summarizes the findings.

$$
\begin{aligned}
\Delta D^{fx}_{i,t} &= \mu_i + \delta_y + \sum_{l=1}^{p} \alpha_l \Delta D^{fx}_{i,t-l} + \sum_{m=0}^{p} \beta_m \Delta D^{cds}_{i,t-m} + \varepsilon_{i,t} \\
\Delta D^{cds}_{i,t} &= \mu_i + \delta_y + \sum_{l=1}^{p} \gamma_l \Delta D^{cds}_{i,t-l} + \sum_{m=0}^{p} \xi_m \Delta D^{fx}_{i,t-m} + \varepsilon_{i,t}
\end{aligned} \tag{14}
$$

where μ_i and δ_y are country and year fixed effects and p is the number of lags of the differenced series to be included in the model.

Table 8: Price discovery

	6-month		1-year		2-year		5-year	
	$\Delta D^{fx}_{i,t}$	$\Delta D^{cds}_{i,t}$	$\Delta D^{fx}_{i,t}$	$\Delta D^{cds}_{i,t}$	$\Delta D^{fx}_{i,t}$	$\Delta D^{cds}_{i,t}$	$\Delta D^{fx}_{i,t}$	$\Delta D^{cds}_{i,t}$
$\Delta D^{fx}_{i,t-1}$	0.22***	0.01	0.13***	0.01	0.30***	0.04	0.42***	0.05
	(0.05)	(0.01)	(0.05)	(0.02)	(0.05)	(0.03)	(0.05)	(0.04)
$\Delta D^{cds}_{i,t-1}$	0.68***	0.16***	0.43***	0.17***	0.33***	0.16***	0.21***	0.24***
	(0.25)	(0.05)	(0.16)	(0.05)	(0.10)	(0.05)	(0.06)	(0.05)
No. of Obs.	1,247		1,247		1,236		1,244	

Note: This table presents a demeaned PVAR for weekly changes of an Arrow-Debreu claim on US dollar CDS and weekly changes of an Arrow-Debreu claim on a portfolio of 10-5 delta FX options for different maturities. Null hypothesis: Slope coefficient = 0. Significance: *** p<0.01, ** p<0.05, * p<0.1. Currency and year fixed effects are included and standard errors are shown in the parenthesis. Choice of lag is based on AIC and BIC statistics.

The coefficients on the lagged price changes of the CDS-based ADCs are significant (at the 1%), whereas the coefficients on the lagged price changes of the FX-based ADCs are insignificant, confirming that the sovereign credit market informs (leads) the FX options market and has a significant impact on market expectations of exchange rates, even at a weekly frequency. The magnitude is substantial and diminishes as the term to maturity lengthens, which makes sense given the increased number of factors that may affect the long-run expectations of exchange rates, including uncertainty about diverging monetary policies. The findings also highlight the interconnectivity of information flow between FX options and sovereign credit markets, which could be a source of significant concentration risk for international portfolio managers seeking diversification.

8 Conclusions

I propose and empirically test a no-arbitrage framework connecting two seemingly unrelated markets: sovereign credit and FOM FX options. I employ a novel approach to identifying and quantifying currency crash and sovereign default risks, which are notoriously difficult to measure. Because currency crashes and sovereign defaults are uncommon disaster states of the world, researchers have limited data. Rather than examining scarce historical data on rare disaster events, I use asset prices of instruments directly related to these states of the world to identify the risk-neutral distribution of these events. I then build a no-arbitrage model around the features already documented in the literature—when a sovereign country defaults on its foreign debt, the country's LC inevitably crashes in value, generating higher volatility, resulting in higher volatility, negative skewness, and a fatter tail in the conditional distribution of currency exchange returns, which is reflected in FX option prices.

I show that a claim on a portfolio comprised of a spread between two co-terminal FOM options is equivalent to a claim on a pure sovereign credit insurance contract. The key sufficient condition for obtaining this result is that a local currency depreciation happens concurrently to a sovereign default. This assumption cannot be rejected by the empirical evidence in the paper. Surprisingly, the cost of these FOM options is often higher than the cost of a CDS contract. As a result, even after accounting for liquidity and transaction costs, a five-year trade crossing the two markets, on average, offers a 3.55% in profit per week and an annualized Sharpe ratio of 7.2. Furthermore, the evidence suggests that the quanto discount price is related to the occurrence of these cross-market deviation opportunities. In turn, the the distance to currency crash and the default intensity shape the quanto discount price. Finally, in a price discovery, the information flows from the sovereign credit market to the FOM FX options market.

The findings of this paper contribute to how one views sovereign credit risk and its connection to FOM FX option markets through the lens of tail risks. The findings also sheds light on a new method of insuring sovereign risk through the use of foreign exchange options. Furthermore, the identified potential cross-market profit opportunities have implications for market efficiency and open the door to further research on limits to arbitrage similar to those studied in the CIP violation literature. Besides, the paper provides a novel method of quantifying the risk-neutral probability of currency crash conditional on default from FOM option prices as well as isolates the expected currency crash size from it. Finally, it reveals that the relationship between the two markets has implications for the pricing the LC relative to FC sovereign debt, an important issue for global international capital flows concerning both international sovereign borrowers and investors.

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APPENDIX: CHAPTER I

A Mapping Collateralization to Funding Rates

For those readers interested in developing an intuition for how the collateral rental yield, which measures the opportunity cost of collateralization, is generally mapped into funding (discounting) rates when pricing collateralized derivatives and when the collateral is in a domestic versus a foreign currency, I sketch a non-formal simple example based on no-arbitrage arguments for how a borrower evaluates their funding when issuing collateralized versus uncollateralized debt and when the collateral for it is in a domestic versus foreign currency. The no-arbitrage is backed by hedge (replication) policy arguments. 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 1, 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 no-arbitrage 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.

However, when the counterparty issues a fully colateralized zero-coupon bond in a foreign currency that must be collateralized in the same foreign currency, a collateral posting is required, and thus the aforementioned replication is not applicable for no-arbitrage to hold. This is 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 1, 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 then 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.[1]

Different from the previous example, when the collateral posting is required in one currency, for instance, the domestic currency ($) (rather than the foreign currency as earlier), but the bond is issued in the foreign currency, (€), denoted $D^{€/\$}_{t}$ here, then the no-arbitrage 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:

$$\frac{D^{€/\$}_{t}}{S_t} \times e^{o^{\$}_{t+1}} \times F_{t+1} = €1 \tag{1}$$

where F_{t+1} is the $t+1$ maturing forward rate of currency ($) per 1 unit of currency (€). Because, in

[1]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.

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:

$$
\begin{aligned}
D_t^{€/\$} &= e^{-o^{\$}_{t+1} - r^{€}_{t+1} + r^{\$}_{t+1}} \\
&= e^{-(r^{€}_{t+1} - y^{\$}_{t+1})} \\
&= e^{-(o^{€}_{t+1} + y^{€/\$}_{t+1})}
\end{aligned}
$$

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 $o^{€}_{t+1}$.

B Considerations on Cross Currency Swaps

The following section relies on a theorem derived in Fujii, Shimada, and Takashi review in the Numerix primer (2012). It is a general theorem for pricing derivatives collateralized in a different currency than their payoff and it is as follow.

Theorem 1. When the collateral is posted in foreign currency (i), the present value of a fully collateralized derivative, h_0, in the domestic currency, (\$), paying h_T at time T is:

$$
\begin{aligned}
h_0^{\$} = E_0^{Q^{\$}} &\left[h_T^{\$} \quad exp\left(-\int_t^T r^{\$}(s)ds \right) exp\left(\int_t^T y^i(s)ds \right) \right] \\
= E_0^{Q^{\$}} &\left[exp\left(-\int_t^T o^{\$}(s)ds \right) h_T^{\$} \quad exp\left(-\int_t^T [y^{\$}(s) - y^i(s)]ds \right) \right]
\end{aligned}
$$

where $E_0^{Q^{\$}}[\cdot]$ is the time t conditional expectation under the risk-neutral measure of currency (\$), where the money market account of currency (\$) is used is used as a numeraire.

The pricing of a Libor 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 foreign currency (e.g. foreign currency leg) that is exchanged at the current spot FX exchange rate (market condition). Adapting the methodology from Fujii, Shimada, and Takahashi (2010) and 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:

$$h_0^{\$} = -1 + D^{\$}(0, T_N) \sum_{n=1}^{N} \delta_n D^{\$}(0, T_n) E^{T_n^{\$}}[L^{\$}(T_{n-1}, T_n)] \tag{2}$$

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) zero-coupon discounting rates.

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

$$h_0^{i} \approx -1 + D^{i/\$}(0, T_N) + \sum_{n=1}^{N} \delta_n D^{i/\$}(0, T_n) E^{T_n^{i}} \left([L^{i}(T_{n-1}, T_n)] + x_n^{Libor}\right) \tag{3}$$

where $D^{i/\$}(0, \cdot) = e^{-\int_0^{\cdot} o^{i}(s)+y^{i/\$}(s)ds}$, x_n^{Libor} is the Libor-based "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.[2]

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:

$$S_0 \times h_0^{\$} = h_0^{i} \tag{4}$$

obtaining the pricing of a collateralized xccy swap, where the collateral is posted in US dollars (\$).

[2]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 $y^{i/\$}$.

The Libor 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 done by re-calculating the xccy basis swap price using Eq. (2), (3), and (4) 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 synthetically calculated OIS-based xccy basis swap prices.

B.1 Constructing Synthetic OIS-Based Cross Currency Swaps

To create the synthetic OIS-Based xccy swaps, I follow the steps below for each month and each currency pair in the sample. First, I calibrate the OIS curve, $[o(T_{n-1}, T_n)]$, from market prices of OIS swaps and the collateralized Libor curve, $[L(T_{n-1}, T_n)]$, from market prices of interest rate (IRS), tenor, and OIS swaps (explained in detail further). I then combine the extracted collateralized Libor and OIS curves with the market prices for the xccy basis, x_n^{Libor}, in the xccy swap pricing, Eq. (2) and (3), and evaluate the market condition with Eq. (4). This step allows me to extract the xccy collateral rental yield curve, which is the only unknown I solve for.

So far, I've extracted three yield curves: the collateralized Libor curve, the forward OIS curve, and the xccy collateral rental yield curve. I discard the collateralized Libor curve, leaving only the OIS and the xccy collateral rental yield curves. Second, I reintroduce the OIS and xccy collateral rental yield curves into Eq. (2) and (3). In the same equations, instead of Libor curves, $[L(T_{n-1}, T_n)]$, I substitute for OIS curves, $[o(T_{n-1}, T_n)]$. Finally, in Eq. (4), I evaluate the market condition and obtain as an output the only unknown I solve for, which is the price of the OIS-based xccy basis, which I denote as x_n^{OIS} and use in the long horizon empirical analysis of the study.

B.2 Further Details on Extracting Libor and OIS yield curves

The detailed procedure employed for extracting the term structure of the Libor and OIS yield curves by stripping observable interest rate multi curves sequentially from xccy[3], OIS and interest rate swaps data. The methodology is is presented below and is adapted and modified from Fujii, Shimada, and Takahashi (2010) and is as follows.

First, I extract two sets of curves from OIS and interest rate swap prices and complement them to a third curve on xccy basis prices that I have readily observable data on. I then fit those curves to the risk-neutral xccy basis pricing identities (2) and (3) imposing the no-arbitrage market condition (4) developed in the main paper. The following are the sets of curves:

1. The first set of curves is composed of one domestic ($) currency discounting curve and one foreign (i) currency OIS discounting curve, which for each currency, is the curve linked to the CSA collateral account rate - FedFunds (OIS) in USD; Eonia (OIS) in EUR, Sonia (OIS) in GBP, etc. Here I obtain the set of zero coupon contractual collateral rates (term structures) $o(0,\cdot)$.

2. The second set of curves is composed of one domestic ($) currency collateralized forward Libors curve and one foreign (i) currency collateralized forward Libors curve, which for each currency is the 3-month Libors curve obtained from single-currency standard interest rate swaps adjusted for 6m vs. 3m tenor swap bases. Here I obtain the set of collateralized

[3] There are two types of xccy-based swaps: a constant-notional swap and an MtM-notional FX reset swap. In a constant-notional swap, the notionals of both legs are fixed at the inception of the trade and kept constant until contract expiry. However, in an MtM FX reset swap, the notional of the US dollar currency leg is adjusted to that of the non-US dollar currency leg at every Libor fixing time using the prevailing spot FX exchange rate. Market standard cross-currency swaps trade on an MtM-notional FX reset basis post the GFC.

forward 3-month Libors (term structures) $L(T_{n-1}, T_n)$ at each T_{n-1} and maturing at T_n.

3. The third is the single curve (term structure) of the quoted Libor-based xccy basis prices, $x(0, \cdot)$, which is readily available in the data, hence no extraction is necessary.

I extract the set of curves (1) and (2) above for every currency and for every month in the data sample as follows.

B.2.1 Extracting the OIS discounting curves (1) from Overnight Index Swaps

To obtain the first discounting curve mentioned above, i.e. $o(0, \cdot)$, I extract it from OIS swaps in each currency individually and use OIS swap prices data. An OIS swap exchanges a fixed coupon for a compounded overnight rate (e.g., FedFunds in USD, Eonia in EUR, etc.). Assuming the OIS swap is continuously collateralized by the same currency it is traded in, based on the framework, for a single currency, the market condition of T_N-maturing OIS rate is as follows:

$$OIS_N \sum_{n=1}^{N} \Delta_n E_t^Q[e^{-\int_0^{T_n} o(s)ds}] = \sum_{n=1}^{N} E_t^Q[e^{-\int_0^{T_n} o(s)ds}(e^{\int_{T_{n-1}}^{T_n} o(s)ds} - 1)] \tag{5}$$

Here the fixed rate OIS_N is the market quote of par rate for the length-N OIS rate, $o(t)$ is the overnight collateral rate (e.g., Fed Funds in USD) at time t and Δ_n denotes a day-count fraction for the fixed leg regarding the period $[T_{n-1}, T_n]$. E_t^Q is the risk-neutral measure at time t where the money market account:

$$\beta(t) = exp(\int_0^{\cdot} r_s ds) \tag{6}$$

is used as a numeraire. Note that I have converted the overnight rate, which uses daily compounding, into continuous compounding for simpler expression.

Furthermore, I can define a collateralized zero-coupon bond as:

$$D(t,T) = E_t^Q[e^{-\int_t^T o(s)ds}] \tag{7}$$

Thus, simplifying equation (5), I have:

$$OIS_N \sum_{n=1}^{N} \Delta_n D(0,T_n) = D(0,T_0) - D(0,T_N) \tag{8}$$

From here, I use an approximate linear technique to extract a smooth curve of the discounting $\{D(0,\cdot)\}$ and their corresponding forward collateral rates $\{o(0,\cdot)\}$ (whole term structure). I repeat the procedure for each currency and each month of the sample.

B.2.2 Extracting the collateralized 3-month Libor rate curves (2)

To obtain the second set of curves (collateralized 3-month Libors curves, $L(T_{n-1},T_n)$), I extract them from Interest Rate Swaps (IRS) and Tenor Swaps (TS) in each currency as follows.

Since the framework assumes that the relevant swaps are collateralized by the same currency they are denominated and traded in, hence I omit the superscripts specifying the currency.

***Step 1: From Interest Rate Swaps**

In an IRS, counterparties exchange a fixed coupon for a strip of Libors with a given frequency. It is important to note that the usual convention for IRS frequency is 6-months Libor, as opposed to xccy swap where the convention is 3m Libor. Therefore, I will need to adjust for 3m vs. 6m Libor tenor bases in step 2. For an IRS that matures at time T_M, I have the following market condition:

$$IRS_M \sum_{m=1}^{M} \Delta_m D(0, T_m) = \sum_{m=1}^{M} \delta_m D(0, T_m) E^{T_m}[L(T_{m-1}, T_m)] \tag{9}$$

Here, IRS_M is the market IRS quote and m represents 6-months. From the OIS extraction earlier, I already know the term structure of $D(0, \cdot)$ curves, and so therefore I extract the set of forward Libors, $[L(T_{m-1}, T_m)]$, for each T_m from the equation above, by just plugging it the $D(0, \cdot)$s. Note that, I end up extracting the set of 6-months Libors, $[L(T_{m-1}, T_m)]$. However, because xccy swaps, as a market standard, exchange 3-month Libors, I need the set or forward 3-month Libors. I obtain those next by using 6-month for 3-month tenor Libor swaps[4].

Note that I have created a collateralized forward measure where the Radon-Nikodym density is given by:

$$\frac{dT_m}{dQ} = \frac{D(t, T_m)}{\gamma(t) D(0, T_m)} \tag{10}$$

where:

$$\gamma(t) = exp(\int_0^t o_s ds) \tag{11}$$

I have to compensate the dividend yield $y = r - 0$ (collateral opportunity cost in each currency) of the collateral zero bond $D(0, T_m)$ in order to make the ratio of numeraire a martingale, an adjustment that changes the β to γ in the Radon-Nikodym density. In simple terms, the extracted set of forward Libors are collateralized forward Libors.

***Step 2: Adjustment with Tenor Swaps**

A tenor swap is a floating-vs-floating swap where the parties exchange Libors of different tenors

[4]Note that this last step is important because ever since the GFC, there are non-trivial bases between 6-month and 3- month Libors and those bases should be taken into account when building a multi-curve xccy swaps pricer.

with a fixed spread (called TS basis) on the short tenor side. For instance, in a 3-month to 6-month tenor swap, parties exchange quarterly payments of 3-month Libor plus a spread for semi-annual payments of 6-month Libor. The market condition that the TS must satisfy is:

$$\sum_{n=1}^{N} \delta_n D(0, T_n) E^{T_n}[L(T_{n-1}, T_m) + TS_n] = \sum_{m=1}^{M} \delta_m D(0, T_m) E^{T_m}[L(T_{m-1}, T_m)] \tag{12}$$

where $T_N = T_M$ (both legs have same maturity) and "*m*" and "*n*" distinguish the difference of payments frequencies as well as the tenor. In this case "m" is 6-months and "n" is 3-months. TS_N denotes the market quote of the basis spread for the T_N-maturing tenor swap. From the above relation, by plugging the set of extracted collateralized forward 6-month Libors from the previous section, I extract the set of collateralized forward 3-month Libors. With this, I have all the curves needed to evaluate identities (2) and (3) imposing the no-arbitrage market condition (4) in order to obtain the term structures of the extracted xccy collateral rental yields and construct the synthetic OIS-based xccy basis prices. I repeat the previous procedure for each currency and each month in the data sample.

C Data Appendix

I provide further details on the data and data sources used in the paper. Detailed Bloomberg tickers of the data series can be found in the spreadsheet online.

Exchange Rates: Daily spot exchange rates and forward points come from Bloomberg using London closing rates for G7 currencies. Mid-rates (average of bid and ask rates) are used for benchmark basis calculations.

Libor Interbank Rates: I use the following Libor benchmark interest rates from Bloomberg for the sample currencies: Australian dollar (AUD): Bank Bill Swap Rate (BBSW); Canadian dollar (CAD): Canadian Dollar Offered Rate (CDOR); Swiss franc (CHF): London Interbank Offered Rate (LIBOR); Euro (EUR): Euro Interbank Offered Rate (EURIBOR); British pound (GBP): LIBOR; Japanese yen (JPY): Tokyo Interbank Offered Rate (TIBOR). I follow the market day count conventions for these interest rates: 365/ACT for the commonwealth currencies (AUD/CAD/GBP), and 360/ACT for the other currencies.

OIS rates: The index rate of the OIS swaps used is typically the rate for overnight lending between banks, either non-secured or secured: Canadian dollar (CAD): CORRA; Swiss franc (CHF): SARON; US dollar (USD): Federal funds rate; Euro (EUR): EONIA; British pound (GBP): SONIA; Japanese yen (JPY): TONAR.

GC Repo rates: US, Swiss franc and Japanese yen mid repo rates come from the Bloomberg. The mid rates are very close to the daily GC repo quotes from BNP Paribas. The euro mid repo data are based on German bunds as collateral and are obtained from BNP Paribas. I do not use Bloomberg euro GC repo rates because eligible collateral also includes sovereign bonds in other European countries besides the German bunds and there are much more stale observations.

According to Baklanova, Copeland, and McCaughrin (2015), in 2015, the total size of the US repo market was estimated to be around \$2.2 trillion, out of which \$1.5 trillion of repos based on GC collateral. According to Sato (2015), the Japanese repo market was about \$1 trillion out of which \$ 0.5 trillion GC repos. According to survey results by the International Capital Markets Association (ICMA, 2016) , the size of the repo market in Europe is about \$3 trillion. The Swiss franc repo markets is much smaller, with a size of less than \$ 75 billion.

Repo contracts are generally characterized by having lending rates and haircut rates applied to the collateral. However, there are no haircuts for GC repo contracts involving Treasuries in Japan and Switzerland. In the U.S., GC repos traded under the Fixed Income Clearing Corporation's (FICC) GCF services also have zero haircuts. Haircuts exist for euro GC repo contracts, but they appear very small. Based on Du, Tepper and Vedherlan (2018), throughout the sample period, the haircuts on German bund collateral changed slightly only once in 2013. Prior to that, haircuts on German Treasury collateral for the remaining maturity brackets are 0.5% (0 to 1 years), 1.5% (1 to 3 years), 2.5% (3 to 5 years), 3% (5 to 7 years), 4% (7 to 10 years), and 5.5% (≥10 years). On July 17, 2013, the ECB changed haircuts on German Treasury collateral to 0.5% (0 to 1 years), 1 (1 to 3 years), 1.5% (3 to 5 years), 2% (5 to 7 years), 3% (7 to 10 years), and 5% (≥10 years).

DTCC transactional data: On December 31, 2012, the Commodity Futures Trading Commission (CFTC) implemented mandatory real-time reporting and public dissemination of OTC swap trades as part of the Dodd-Frank Wall Street Reform and Consumer Protection Act. Swap transactions must be reported to a recordkeeping facility known as a swap data repository (SDR), which then disseminates transaction details to the public (e.g., trade price, trade size, timestamp, and trade characteristics related to the Dodd-Frank reforms).

As a result, I was able to obtain 459,143 reports of cross-currency basis swap derivatives trades executed between January 1, 2013 and March 31, 2020, which are publicly distributed by the Depository Trust & Clearing Corporation (DTCC) Data Repository (U.S.) LLC (DDR). Each DDR report contains a numeric identifier (DISSEMINATION ID), an execution timestamp, a price, a trade size (expressed as the notional amounts of each leg of the swap), a currency 1 denomination, a currency 2 denomination, a collateralization indicator, a clearing indicator, and other contract characteristics.[5]

A trade report specifies the notionals of a cross-currency swap trade as notional 1 for the first leg and notional 2 for the second leg, as well as the settlement currency. I only keep G-7 currencies against the USD, which are EUR, JPY, GBP, CHF, AUD, CAD. As a result, the sample size is reduced to 387,719 transaction reports.

Furthermore a report indicates a new trade, cancel a previous report, or correct a previous report. To cancel a previous report, the reporting entity files a cancellation report that identifies the original report to be canceled. To correct a report, the reporting entity must not only cancel the original erroneous report but also file a new report with the correct information (correction report). Like the cancellation report, the correction report also indicates the original report's identifier. I use this reporting protocol to perform an initial cleaning of the data. First, I remove duplicate reports (i.e., reports with the same identifier). Next, I remove canceled reports and cancellation reports. Finally, I remove the correction reports duplicate correction reports and correction reports that cannot be linked to the original reports due to a missing identifier for the original transaction.

Furthermore, I notice large unusual isolated outliers in the data field indicating the price of cross-

[5] DDR's Real Time Dissemination Dashboard User Guide provides a complete list of data fields in publicly disseminated trade reports (https://pddata.dtcc.com/gtr/cftc/dashboard.do).

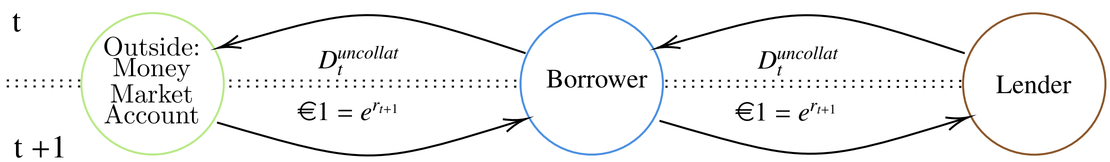
currency swap transactions in the reports, which could be due to data entry errors. As a result, I limit the sample to prices within 4 standard deviations of the mean. This completes the cleaning process and reduces the sample from 459,143 to 219,713 new reports, all of which are new trades rather than novations of old trades, on which I will concentrate.[6]

[6]The CFTC also requires swaps entered into prior to December 31, 2012 to be reported (historical swaps). I found 85,036 historical swap trade reports in our sample. I exclude these trades from our analysis due to the possibility of inconsistent reporting.

Figure 1: No-arbitrage replication for a Borrower (Issuer) of a Collateralized Zero Coupon Bond

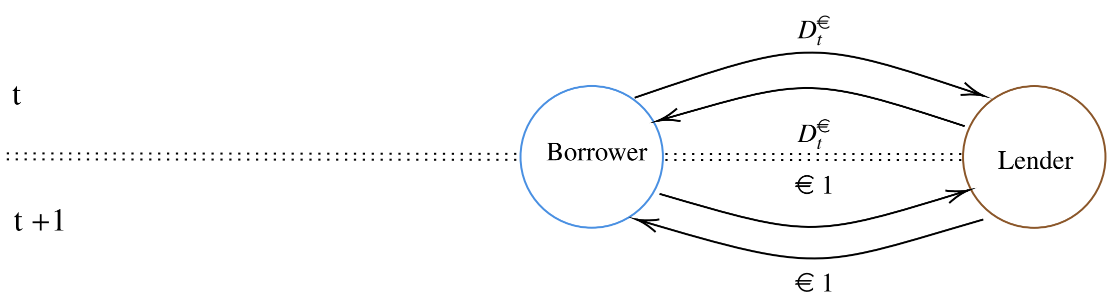
This diagram illustrates the cash flows of a non risky counterparty issuer associated with issuing a zero coupon (ZC) bond that is not collateralized ($D_t^{uncollat}$) in Panel A, a zero coupon bond that is collateralized in the same currency, €, of the issued bond itself ($D_t^{€}$) in Panel B, and 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



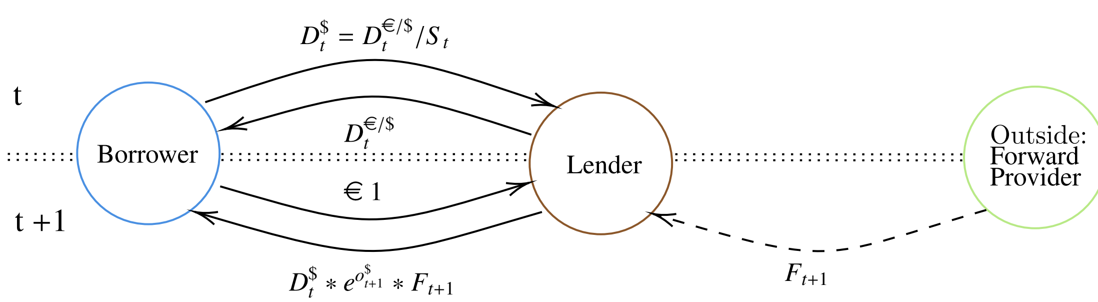
No-arbitrage brake-even present value of ZC bond: $D_t^{uncollat} = e^{-r_{t+1}}$

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:

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

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APPENDIX: CHAPTER II

A Extra Tables and Robustness Checks

Table 1: Summary statistics for CDS bid-ask spreads

	Mean	Median	Min	Max	Std	N
All Countries						
CDS bid-ask spread (as fraction of mid)	0.10	0.08	0	0.74	0.07	1680
AUDUSD						
CDS bid-ask spread (as fraction of mid)	0.07	0.07	0	0.16	0.02	560
GBPUSD						
CDS bid-ask spread (as fraction of mid)	0.16	0.15	0.04	0.74	0.08	560
USDJPY						
CDS bid-ask spread (as fraction of mid)	0.08	0.07	0	0.34	0.05	560

Note: This table presents summary statistics for the bid-ask spread of 5-year CDSs (as a fraction of its mid price) for the whole sample period.

Table 2: Time series relationship between Arrow-Debreu claims (ADCs) with higher FX option delta barriers

	6-month	1-year	2-year	5-year
Dep. Var.: Δ of claim on 15-10 delta FX puts	$\Delta D^{fx(15-10\delta)}$			
Panel A: Including country and year fixed effects				
ΔD^{cds} (β)	1.20	0.53***	0.58***	0.34***
t-stat	(0.8)	(-3.13)	(-6.00)	(-13.2)
Within Adj-R^2	0.01	0.01	0.03	0.02
Panel B: No fixed effects				
ΔD^{cds} (β)	1.19	0.54***	0.59***	0.35***
t-stat	(0.73)	(-2.88)	(-5.86)	(-13.00)
Within Adj-R^2	0.01	0.01	0.03	0.02
No. of Obs.	5,347	5,365	4,826	5,138

Note: This table presents panel regressions of weekly price changes of an Arrow-Debreu claim on a portfolio of 15-10 delta FX options ($\Delta D^{fx(15-10\delta)}$) on price changes of an Arrow-Debreu claim on a CDS (ΔD^{cds}) for different maturities testing the Null hypothesis of $\beta = 1$. Two-tailed t-stats are calculated under the Null hypothesis that $\beta = 1$ based on robust (two-way for the Panel B clustered by currency and time) standard errors and are shown in parenthesis. Significance: *** p<0.01, ** p<0.05, * p<0.1. ADF, PP, and KPSS tests indicated that the FX-based ADC series are non-stationary and integrated of order one, thus, for clean identification regressions are in first differenced variables.

Table 3: Cross-market deviations when FX option delta barriers are higher

	6-month	1-year	2-year	5-year
$\mathcal{R}$ uses 15-10 delta FX puts	$\Delta\mathcal{R}_{i,t} = \Delta(D_{i,t}^{fx(15-10\Delta)} - D_{i,t}^{cds})$			
$\Delta Q_{i,t}^{(D^{i,cds}-D^{usd,cds})}$ (ψ)	1.19	1.50**	0.79***	0.20***
	(0.76)	(0.55)	(0.15)	(0.05)
$\Delta FX_{i,t}^{spot}$ (δ)	-0.04***	-0.02***	-0.03***	0.02**
	(0.01)	(0.01)	(0.01)	(0.01)
$\Delta IV_{i,t}^{ATM}$ (υ)	0.01***	0.02***	0.02***	0.04***
	(0.00)	(0.00)	(0.01)	(0.00)
$\Delta US_{i,t}^{OIS}$ (ρ_1)	-0.01***	-0.01***	-0.01***	-0.01***
	(0.01)	(0.00)	(0.00)	(0.00)
$\Delta Local_{i,t}^{OIS}$ (ρ_2)	0.02**	0.01***	0.01***	0.02***
	(0.01)	(0.00)	(0.00)	(0.00)
$\Delta Basis_{i,t}^{xccy}$ (γ)	0.00	0.00	0.00	0.00**
	(0.00)	(0.00)	(0.00)	(0.00)
Within Adj-R^2	0.15	0.18	0.26	0.23
No. of Obs.	1,840	2,764	2,714	2,875

Note: This table presents panel regressions of weekly changes in the cross-market deviations ($\Delta\mathcal{R}$) using a portfolio of 15-10 delta FX options on changes in the quanto spread (ΔQ) and other variables. The null hypothesis is that each slope coefficient is equal to zero. Significance: *** p<0.01, ** p<0.05, * p<0.1. Currency and year fixed effects are included and robust, two-way clustered standard errors by currency and time are shown in the parenthesis.

B Link between CDS and ADC

The following analysis is adapted from Carr and Wu (2011) and examines how Arrow-Debreu Claim (ADC) values are linked to CDS spreads in a fair no-arbitrage way. Let $V(t,T)$ denote the time-t value of the protection leg of a CDS contract with expiry T and R denote the fixed recovery rate on the sovereign bond in the event of default. It pays $1-R$ at the time of default τ if $\tau \leq T$ and zero otherwise. The recovery rate on sovereign bonds is generally unknown ex-ante, and it varies depending on the bond and the default situation. Nevertheless, swaps on the recovery rate of sovereign bonds on default are quite actively traded nowadays. As a result, recovery swaps can be used to remove the uncertainty in the bond recovery in the CDS contract.

Moreover, when relating CDS to ADC, the link will be dependent on the underlying assumptions made. Consider the following three cases.

Case 1: Assuming that the recovery rate R is known and fixed. Then the payoff of the protection leg of the CDS is simply $1-R$ times the payoff of a ADC. No-arbitrage implies that:

$$V(t,T) = (1-R)D^{CDS}(t,T) \tag{1}$$

where the Arrow-Debreu Claim (ADC) is denoted as $D^{cds}(t,T)$.

Case 2: Assuming that the riskfree rate is a deterministic function of time $r(t)$. Then the value the premium leg of the CDS contract, $z(t,T)$, can also be linked to the whole term structure of ADCs:

$$a(t,T) = z(t,T)E_t^Q \int_t^T e^{\int_t^s (r(u)+\lambda(u))du} ds \tag{2}$$
$$= z(t,T) \int_t^T \left[e^{-\int_t^s r(u)du} - D^{cds}(t,s) + \int_t^s r(u)e^{-\int_u^s r(v)dv} D^{cds}(t,u)du \right] ds \tag{3}$$

where $a(t,T)$ represents the value of a defaultable annuity that pays \$1 per year indefinitely until the earlier of the default time τ and the maturity date T.

Therefore, assuming continuous premium payment until $\tau < T$, the time-t CDS spread of expiry T can be represented as:

$$z(t,T) = \frac{V(t,T)}{a(t,T)} \tag{4}$$

To sum, assuming a known fixed bond recovery rate, R, implies that equation (1) can be used to relate the numerator to the ADC value, $D^{cds}(t,T)$, whereas assuming deterministic interest rates implies that equations (2) and (3) can be used to relate the denominator to a given ADC term structure. With both assumptions satisfied, the CDS spread can be expressed in terms of ADC values for the entire term structure as follows:

$$z(t,T) = \frac{(1-R)D^{cds}(t,T)}{\int_t^T \left[e^{-\int_t^s r(u)du} - D^{cds}(t,s) + \int_t^s r(u)e^{-\int_u^s r(v)dv} D^{cds}(t,u)du \right] ds} \tag{5}$$

As a result of combining Cases 1 and 2, one can extract the ADC term structure from a CDS term structure without assuming how the default occurs.

Case 3: Assuming constant interest rates and default arrival rates (flat CDS term structure).The value of the ADCs can be inferred from a single CDS quote rather than the entire term structure of CDSs. This is the method used in the main paper due to its simplicity.

$$D^{cds}(t,T) = \lambda(t,T)\frac{1 - e^{-(r(t,T)+\lambda(t,T))(T-t)}}{r(t,T) + \lambda(t,T)} \tag{6}$$

where $r(t,T)$ is the deterministic continuously compounded interest rate, $\lambda(t,T) = z(t,T)/(1-R)$ is the constant default arrival rate.

C Computational Details for FX Option Prices

In terms of FX options market conventions, a stylized fact in the OTC market is that FX options are quoted based on their delta (δ) rather than their strike, as is the case in other options markets. According to the BlackScholes assumptions, delta is an approximation of an option's "moneyness." An at-the-money option will have a delta of around 0.5, reflecting a 50:50 probability of expiring in-the-money. Exercise prices for FX options are often described in terms of delta, thus an at-the-money option would be referred to as a 50delta call or put. Furthermore, round percentage point figures like 25delta and 75delta, which reflect near in-the-money and out-of-the-money calls (or close out-of and in-the-money puts) are quite prevalent.

Moreover, it is market standard that the FX options are quoted in terms of Garman and Kohlhagen (1983)-implied volatilities on baskets of options as opposed to a single option, at fixed deltas and with constant maturities. Because those are the only ones available, I get quotes from Bloomberg for nine different FX option combinations: delta-neutral (0δ) straddle (V_{ATM}), 5δ, 10δ, 25δ, and 35δ risk-reversals (RR_δ), and 5δ, 10δ, 25δ, and 35δ butterfly spreads (B_δ).[1] Then, based on a market practice convention, I calculate the plain vanilla delta call (C) or put (P) implied volatilities (V) from data on ATM, straddles, and butterfly implied volatilities using the following formulas:

$$V_{C,\delta} = V_{ATM} + B_\delta + \frac{1}{2}RR_\delta, \qquad \text{for vanilla Calls} \tag{7}$$

$$V_{P,\delta} = V_{ATM} + B_\delta - \frac{1}{2}RR_\delta, \qquad \text{for vanilla Puts} \tag{8}$$

After calculating the implied volatility-delta pairs of the plain vanilla put and call FX options, I am faced with the task of converting delta-volatility to strike-price pairs, which I do next.

I follow Wystup (2010) for the conversion formulas. I first convert the non-premium-adjusted spot

[1] In line with market conventions, for instance, a 5δ call option has a delta of 0.05 and a 5δ put option has a delta equal to -0.05.

delta to a strike. With given delta (δ) and implied volatility (σ), I directly solve for the strike (K) using the equation below:

$$K = fe^{-\phi N^{-1}(\phi e^{r_f \tau}\delta)\sigma\sqrt{\tau}+\frac{1}{2}\sigma^2\tau} \tag{9}$$

where N^{-1} is the inverse of the normal cumulative distribution function, $\phi = +1$ for a call or $\phi = -1$ for a put, f is the FX outright forward rate, and τ is the time to maturity, equal to $T - t$.

I then compute the value of the vanilla option premium using the formula below:

$$v^d = \phi e^{-r_d \tau}\left[f(t,T)N(\phi d_+) - KN(\phi d_-)\right] \tag{10}$$

where S_t is the spot exchange rate, $N(x)$ is the cumulative normal distribution function, r_d is the domestic interest rate (continuously compounded), and $d_\pm = \frac{\ln\left(\frac{f(t,T)}{K}\right)\pm\frac{1}{2}\sigma^2\tau}{\sigma\sqrt{\tau}}$.

The above formula returns a value v^d in the domestic currency, which is US dollars. The value formula applies to one unit of foreign notional with a value in units of domestic currency because the payoff is in domestic currency notional. However, by convention, some currency pairs are quoted in foreign currency as their option payoff is in foreign currency notional. In order to convert their option premiums in domestic currency, US dollars, I can't simply use the v^f/S_t due to an otherwise embedded inconsistency. Instead, I use:

$$v^d = \frac{1}{K}\frac{v^f}{S_t} \tag{11}$$

To understand why, consider the perspective of a foreign investor who exchanges one unit of foreign currency for K units of domestic currency (US dollars). For example, this is the party that pays in foreign currency and receives in domestic currency. Typically, the domestic investor receives one foreign currency unit and pays K domestic (US dollar) units. Hence, the foreign investor receives K units of the domestic currency (US dollars), not one. As a result, in order to obtain the option premium in US dollars, v^d, I must adjust the exchange of amounts so that the foreign investor receives one unit of domestic currency rather than K. This can be accomplished by paying 1/K foreign currency units rather than one, which is equivalent to adjusting the foreign notional by 1/K rather than one. When the domestic party receives 1/K of a foreign currency unit, the equivalent domestic amount paid is $(1/K) \times K = 1$. This shows that, as desired, following the adjustment, the foreign investor receives one domestic currency unit (1 US dollar). The domestic (US dollar) currency price of the premium, v^d, is then expressed by resetting the foreign notional to $N^f = 1/K$ and converting the option premium of the foreign currency.

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