Sovereign Defaults and Currency Crashes: Insurance and Quanto[*]

Ljubica Georgievska[†]

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Abstract

To what extent are currency crashes linked to 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 segmentation, 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.

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

Keywords: Exchange rates, CDS, Options, Sovereign default risk, Quanto.

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[†]Anderson School of Management, UCLA. Web: https://sites.google.com/view/ljubicageorgievska/home

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 periods.[2] As a result, understanding the covariance between these markets and how it evolves over time is critical. However, a measurement roadblock arises

[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.

[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).

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.

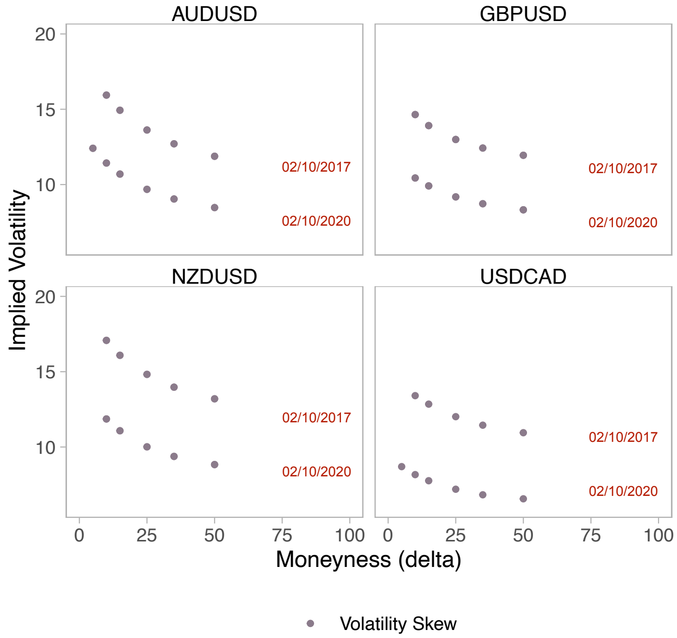
When a sovereign defaults on its foreign debt, the country's LC inevitably crashes in value, resulting in higher volatility, negative skewness, and fatter tails in the conditional distribution of exchange rate returns. This skewness is manifested in the pricing of currency options at sufficiently FOM 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 synthesizing 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

[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).

[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.

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

(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 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 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

[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.

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 depreciation 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

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

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 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,

[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.

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 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 Internet 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.

[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.

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 $P_t(K_1, T)$ struck within the default corridor are available, one can infer the value of the CDS-based ADC from them:

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

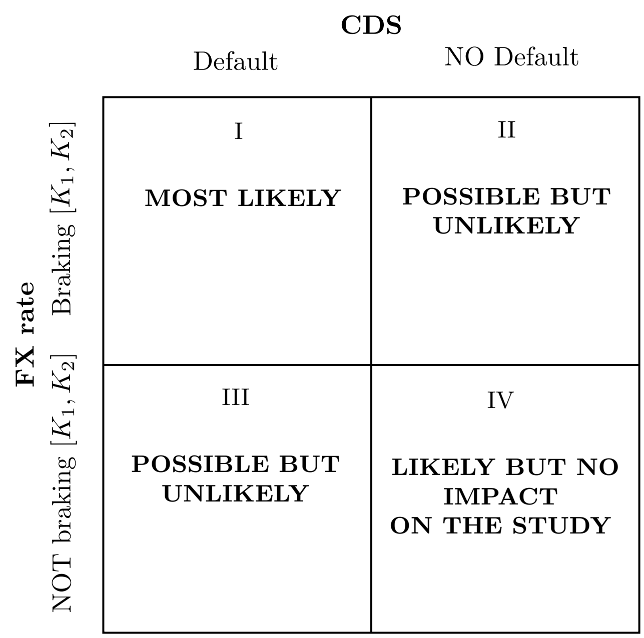
where cds and fx denote the information source as CDS-based and FX-based, respectively.

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

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.

Figure 2: Matrix of outcomes



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.

The FX rate could fall below the FOM lower strike put without triggering a CDS default (partition II). 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 aggressive 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 III), 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 I).

The simple framework of this paper is based on the plausibility of partition I 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.

[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.

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:

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

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 currency 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.

[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.

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. Internet 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

[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.

put spread using Eq. (3), and another ADC value from a CDS spread on the sovereign bonds using Eq. (4) under the assumption 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 Internet 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.

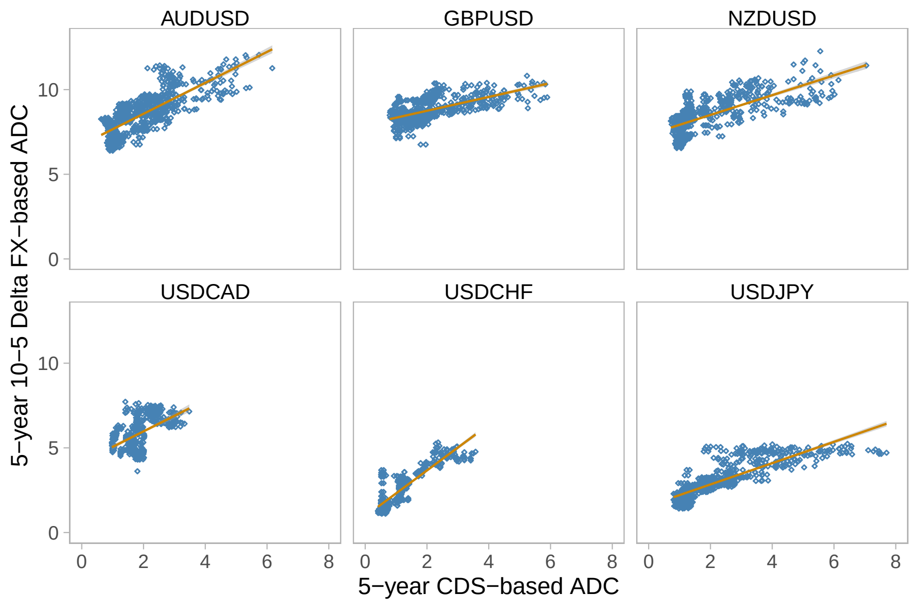
7 Results

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 an Arrow-Debreu claim on a portfolio of 10-5 delta FX options and an Arrow-Debreu claim on a CDS (ADCs)



Note: Prices are in cents (or %) per 1 US dollar payoff.

Table 1: Cross-sectional correlation between an Arrow-Debreu claim on a portfolio of 10-5 delta FX options and and Arrow-Debreu claim on a CDS (ADCs) for different maturities (weekly frequency)

	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: 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 Internet 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: Panel regressions of weekly price changes of an Arrow-Debreu claim on a portfolio of 10-5 delta FX options ($\Delta D^{fx(10-5\delta)}$) on price changes of an Arrow-Debreu claim on a CDS (ΔD^{cds}) for different maturities testing the Null hypothesis of $\beta = 1$

	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

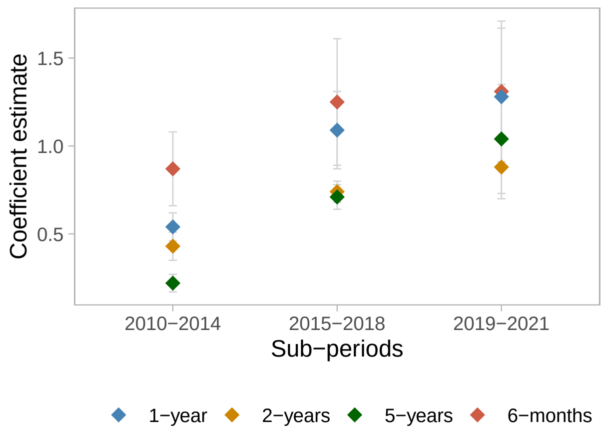
Note: Two-tailed t-stats are calculated under the Null hypothesis that $\beta = 1$ based on robust (two-way for the Panel B clustered by currency and time) standard errors and are shown in parenthesis. Significance: *** p<0.01, ** p<0.05, * p<0.1. ADF, PP, and KPSS tests indicated that the FX-based ADC 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: Coefficients and standard error bands from panel regressions of price changes of an Arrow-Debreu claim on a portfolio of 10-5 delta FX options on price changes of an Arrow-Debreu claim on a CDS (ADCs) for different maturities during three different sub-periods



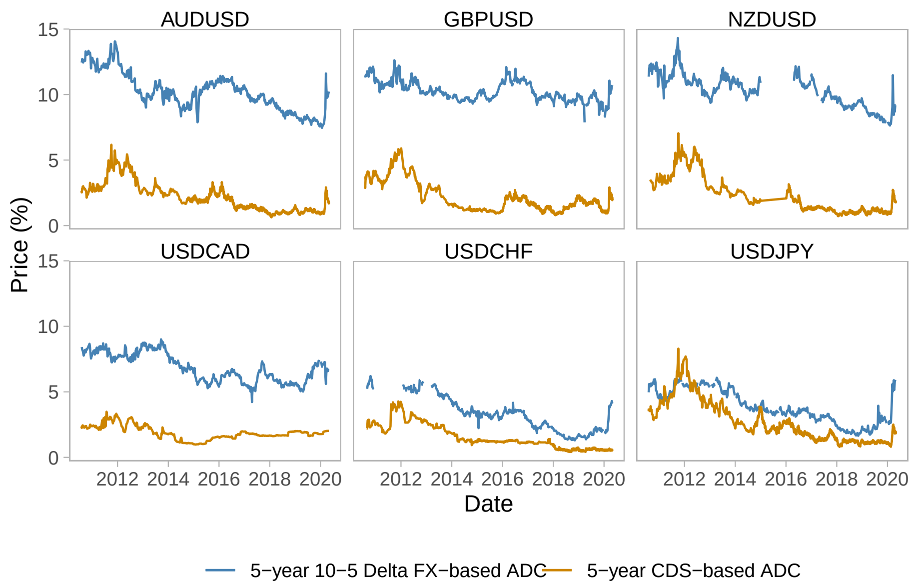
Overall, because FOM options identify the tail of the exchange rate distribution, the above findings cannot reject the key assumption of the framework in this paper, which is that the probability of currency crash depreciation in the event of a sovereign default is fairly constant and one, all the more so for shorter maturity terms and post-2014. This is not the case if the FX-based ADCs are built with insufficiently FOM options, as shown by the robustness checks in Internet 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 relatively large differences in the magnitudes between the two series. This evidence suggests that the hypothesis on the equivalency is partially

[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.

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 an Arrow-Debreu claim on a portfolio of 10-5 delta FX options vs. an Arrow-Debreu claim on a CDS (ADCs)



Note: 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 weekly price levels of a 5-year Arrow-Debreu claim on a portfolio of 10-5 delta FX options ($D^{fx(10-5\delta)}$) and an Arrow-Debreu claim on a CDS (D^{cds}) as well as their cross-market deviation ($\mathcal{R}$)

	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: Prices are in cents (or %) per 1 US dollar payoff.

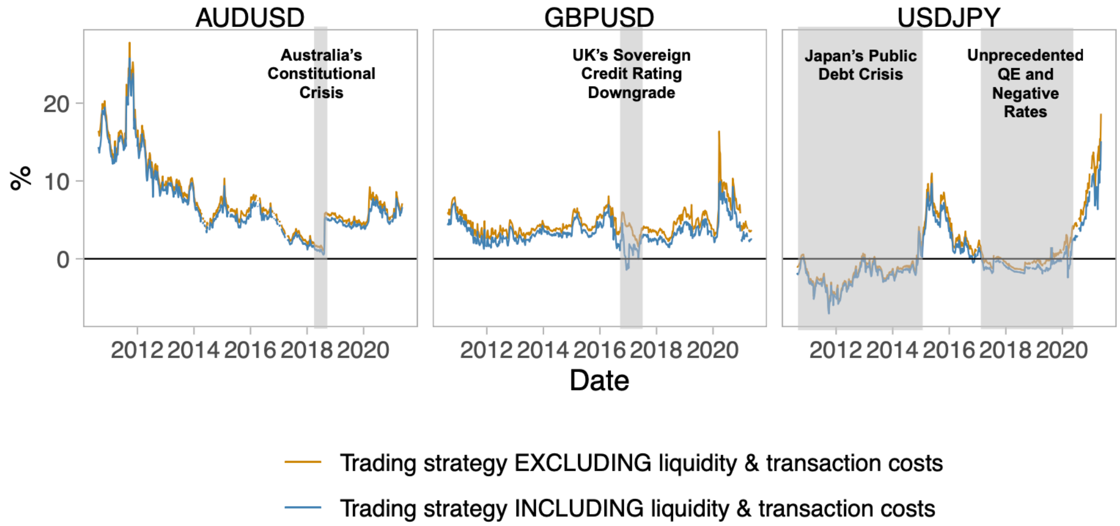
To investigate further, I devise a cross-market trading strategy to exploit this potential profit opportunity, but this time I account for liquidity and transaction costs. Because Markit data on CDS only includes mid prices, I use data on CDS bid and ask prices from Bloomberg instead for this analysis. 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: Potential weekly profitability of a cross-market trade strategy including versus excluding liquidity and transaction costs



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] An interesting observation is that during times of

Table 4: All Countries – Expected profitability of a weekly cross-market trading strategy on the 5-year maturity tenor – Sharpe ratio is annualized

	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: Except Sharpe ratio, prices are in cents (or %) per 1 US dollar payoff per week.

crisis, such as Japan's public debt crisis in 2012, the UK's sovereign credit rating in 2012,

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

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 and Figure 5), 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' 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

[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.

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 Internet Appendix A summarizes the same results but with a cross-market deviation using 15-10 delta struck FOM put options' spread).

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

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.

Table 5: 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

	6-month	1-year	2-year	5-year
$\mathcal{R}$ uses 10-5 delta FX puts	$\Delta\mathcal{R}_{i,t} = \Delta(D^{fx(10-5\Delta)}_{i,t} - D^{cds}_{i,t})$			
$\Delta Q^{(D^{i,cds}-D^{usd,cds})}_{i,t}$ (ψ)	1.62*	1.28**	1.27***	0.72**
	(0.85)	(0.64)	(0.35)	(0.31)
$\Delta FX^{spot}_{i,t}$ (δ)	-0.02	0.00	-0.02	0.01
	(0.01)	(0.01)	(0.01)	(0.03)
$\Delta IV^{ATM}_{i,t}$ (υ)	0.01***	0.00	0.01	0.01
	(0.00)	(0.00)	(0.01)	(0.02)
$\Delta US^{OIS}_{i,t}$ (ρ_1)	-0.02**	-0.01***	-0.00*	-0.01*
	(0.01)	(0.00)	(0.00)	(0.00)
$\Delta Local^{OIS}_{i,t}$ (ρ_2)	0.04**	0.02***	0.00	0.01
	(0.02)	(0.00)	(0.00)	(0.01)
$\Delta Basis^{xccy}_{i,t}$ (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: 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.

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 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.

[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 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)

	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: CDS spreads are in basis points. The quanto spread is calculated as the difference between the LC and US dollar denominated CDS spreads.

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 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 the changes in the quanto discount price on the 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.

$$\begin{aligned}\Delta Q_{i,t} = \alpha_i + \theta_y + \psi\Delta\mathcal{DC}_{i,t} + \xi\Delta D^{cds}_{i,t} + \omega\Delta s^{UIP}_{i,t} + \delta\Delta S^{spot}_{i,t} + \upsilon\Delta IV^{ATM}_{i,t} \\ + \rho_1\Delta OIS^{\$}_t + \rho_2\Delta OIS^{i}_{i,t} + \gamma\Delta Basis^{xccy}_{i,t} + \varepsilon_{i,t}\end{aligned} \tag{13}$$

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.

Table 7: Panel regressions of weekly changes in the quanto discount price (ΔQ) on changes in the distance to crash ($\Delta\mathcal{DC}$) and other variables

	(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: 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.

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 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: 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

	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: 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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