# Risk-Free Rates and Convenience Yields Around the World

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June 4, 2023

Abstract

We infer risk-free rates from index option prices to estimate safe asset convenience yields in 10 G11 currencies. Countries' convenience yields increase linearly with the level of their interest rates, with US convenience yields fifth largest. During financial crises, convenience yields grow, but the difference between US and foreign convenience yields generally does not. Covered interest parity (CIP) deviations using our option-implied rates are roughly the same size between the US and each other country. A model where convenience yields depend on domestic financial intermediaries, but CIP deviations depend on international arbitrageurs funded with wholesale dollar-denominated debt, explains these results.

We thank Max Yang for outstanding research assistance, Jesse Schreger, Jonathan Wallen, Zhengyang Jiang, and Anna Cieslak for comments, and Alyssa Anderson, Wenhao Li, Patrick Augustin, and Wenxin Du for very helpful conference discussions. We also thank the Wharton Dean's Research Fund, Jacobs Levy Equity Management Center, and Rodney White Center for Financial Research for generous financial support. The views expressed in this paper are those of the authors and do not necessarily reflect the position of the Federal Reserve Bank of New York or the Federal Reserve System. Any errors or omissions are the responsibility of the authors.

# 1 Introduction

A key feature of the global financial system is a demand from investors to hold safe assets. Recent work (Krishnamurthy and Vissing-Jorgensen, 2012, Nagel, 2016, van Binsbergen et al., 2021, Jiang et al., 2021, Kekre and Lenel, 2022) shows that investors give up a sizeable return, the "convenience yield," to hold dollar safe assets such as US government debt compared to other dollar investments providing the same cash flows.[1] In addition, investors earn a higher dollar-denominated return by holding foreign safe assets combined with a currency swap than by buying dollar safe assets, violating the covered interest parity (CIP) relationship (Du et al., 2018b, Jiang et al., 2019, Du et al., 2018a). During financial crises, dollar convenience yields and CIP deviations both dramatically spike. A common explanation for these facts is that because US safe assets are denominated in the global reserve currency, they provide a larger convenience yield than foreign ones. This paper directly measures convenience yields in 10 of the G11 currencies. We find that international arbitrage frictions, not a disproportionately large US convenience yield, explains the dollar's behavior.

Our analysis relies on a new database of risk-free rates implicit in index option prices that we argue are free of the convenience yield of safe assets. We infer these rates, which we call box rates, using intraday time-stamped option price quotes on each country's main stock index from 2004 to 2020. Exploiting the put-call parity relationship for European options, we infer risk-free interest rates from our option prices without specifying any particular asset pricing model. Importantly, each individual option is risky and should not provide a convenience yield. However, a portfolio of options called the box trade (Ronn and Ronn, 1989, Avino et al., 2017) yields a risk-free payoff whose price implies the box rate.

We use our box rates to construct two key arbitrage spreads. First, for a safe asset

[1] Gorton and Pennacchi (1990), Bansal and Coleman (1996), Lagos et al. (2017), Diamond (2020) provide theoretical explanations for this convenience yield.

denominated in a given currency, we estimate its convenience yield as the difference between that currency's box rate and the safe asset's interest rate. This convenience yield shows how much interest investors forgo to hold the safe asset relative to an investment with identical payoffs. It is inferred only from assets denominated in the same currency. Second, we take a foreign box rate together with a currency forward to replicate a "synthetic dollar rate" whose payoffs are identical to our dollar box rate. The arbitrage spread between our US box rate and this synthetic dollar rate, that we call a box CIP deviation, measures frictions in international arbitrage. Because box rates are inferred only from risky options, box CIP deviations are not impacted by convenience yields.

A country's average convenience yield for government debt is closely related to the level of its interest rates. A cross-sectional regression of a country's average convenience yield on its average government bond yield has an R-squared of .74, with a 1 percentage point higher rate associated with a 15 basis point higher convenience yield. US convenience yields average 35 basis points, fifth of 10 countries. When nominal interest rates are negative, how far the rate goes below 0 is unrelated to the size of convenience yields. In addition, we consider how a range of other assets' convenience yields vary with the level of interest rates. We find that the more "money like" an asset is, the more its convenience yield increases as rates go up.

We then compare box CIP deviations to CIP deviations using other rates. While box CIP deviations are an arbitrage spread using two countries' box rates, we can construct similar spreads using Treasury yields or any other risk-free rates. The time-series average of each country's box CIP deviation is roughly 10 basis points, suggesting a cost of international arbitrage that does not vary across countries. This is unlike CIP deviations constructed from Treasuries (Du et al., 2018a), LIBOR (Du et al., 2018b), overnight indexed swap (OIS) rates, and savings deposit rates which vary strongly with the level of interest rates in each country. We argue that this is because these other rates reflect convenience yields which also vary with the level of nominal interest rates. The cross-section of CIP deviations for all rates is consistent with a constant cost of international arbitrage between G11 countries together with convenience yields in each country proportional to their level of interest rates.

Next, we examine convenience yields and box CIP deviations over time. Both convenience yields and CIP deviations spike during the 2007-2009 US financial crisis, 2011-2012 Euro crisis, and 2016-2017 Brexit crisis. Convenience yields grow the most in the country where each crisis is centered. On average, foreign convenience yields grow just as much as US convenience yields during crises. In contrast, box CIP deviations between the US and other countries grow in all crises, suggesting that international arbitrage becomes more costly. In the March 2020 Covid crisis, when dislocations in the markets for Treasuries (He et al., 2021) and other bonds (Haddad et al., 2021, Ma et al., 2021) temporarily made US convenience yields negative, box CIP deviations grew as in other crises. We conclude that growing CIP deviations during crises reflect increasing frictions in international arbitrage and do not imply that US convenience yields grow more than than foreign ones.

We next examine the impact of US and European quantitative easing (QE) and the 2015 break of the Swiss Euro currency peg. We find similar results for US QE during its 2008-2009 crisis and for European QE during its 2009-2012 crisis. In both cases, QE reduces domestic convenience yields more than it reduces foreign convenience yields. Both also reduce the US-Euro box CIP deviation. This suggests that QE reduces financial frictions during crises, with a stronger domestic than international impact. The Swiss currency peg break sharply reduced Swiss box and government interest rates with almost no effect on Swiss convenience yields. Because Swiss rates were negative before the break, this provides more evidence that convenience yields are unrelated to the level of interest rates once rates become negative.

Finally, we consider the relationship between CIP deviations, convenience yields, and exchange rates. First, we build on Engel and Wu (2022), who show that government bond CIP deviations are strong predictors of exchange rates. We decompose each country's government bond CIP deviation into a box CIP deviation and the difference between that country's and the US's convenience yield. We show that both box CIP deviations and convenience yield differences forecast exchange rates. Next, we build on Avdjiev et al. (2019), who show that strengthening of the dollar coincides with a widening in CIP deviations. This also holds for box CIP deviations but not for the difference between US and foreign convenience yields. This suggest that the dolllars strengthens when international arbitrage is constrained but not necessarily when convenience yields are larger in the US than in other countries.

We explain our findings in a theoretical model related to Nagel (2016). In the model, consumers obtain reduced-form "liquidity services" from cash and bank deposits. Convenience yields on assets held by financial intermediaries, who use these assets to issue bank deposits, grow proportionately with the deposit convenience yield. When a country experiences a financial crisis, convenience yields in that country grow. In addition, an international financial arbitrageur borrows risk-free in dollars from the US financial intermediary and invests in foreign countries. A CIP deviation emerges between the dollar rate at which the arbitrageur borrows and the strictly higher dollar rate at which it lends in other countries (Boyarchenko et al., 2020, Anderson et al., 2020, Siriwardane et al., 2022). These CIP deviations spike when the international arbitrageur is constrained, like box CIP deviations in the data. The dollar differs from other currencies in the model in one way: international arbitrageurs borrow in dollars and invest in other currencies. This explains why box CIP deviations spike in all crises, while each country's convenience yield is impacted mostly by domestic crises.

Our results clarify how the US is unique in the global financial system. US safe asset convenience yields do not seem particularly large or sensitive to crises compared to other countries. Our CIP deviation results show that there is a global demand for dollar assets which reduces US interest rates, but this impacts all dollar interest rates, including box rates, and therefore does not imply US convenience yields are particularly large. Our evidence does not contradict a large foreign demand for US safe assets from investors such as foreign central banks, but this demand does not result in an unusually large US convenience yield.

**Relation to Literature** This paper contributes first to the literature on measuring the convenience yields of safe assets, which has focused so far on the US (Krishnamurthy and Vissing-Jorgensen, 2012, van Binsbergen et al., 2021, Lenel et al., 2019, Vanderweyer, 2022). Foreign convenience yields (Du et al., 2018a) are inferred directly from international arbitrage spreads, and we believe we are the first to measure each country's convenience yields only from asset prices in that country. Our cross-country evidence that convenience yields increase with the level of interest rates extends work finding similar patterns in US time-series data (Nagel, 2016, Dreschler et al., 2017, Krishnamurthy and Li, 2022).

We contribute to the CIP deviation literature (Du et al., 2018b, Wallen, 2020, Krishnamurthy and Lustig, 2019, Viswanath-Natraj, 2020) using our new convenience yield measures. Previous papers have proposed a decomposition of CIP deviations that include both convenience yields and other international arbitrage frictions (Du et al., 2018a, Augustin et al., 2022), but we are the first to plug observable convenience yields measures into such a decomposition. Most similar to our results are patterns in risky corporate bond yields in Liao (2020), suggesting that his cross-country variation in corporate-Treasury spreads is explained by differences in countries' convenience yields.

Finally, our work contributes to a literature that infers risk-free rates from derivatives. Most papers use futures (Fleckenstein and Longstaff, 2020, Hazelkorn et al., 2023) or interest rate swaps (Feldhutter and Lando, 2008, Fleckenstein and Longstaff, 2022, Jermann, 2020, Du et al., 2022). These respectively require a value for dividends paid before the futures mature and reference a nearly risk-free rate (such as banks' overnight borrowing rates) that may be liquid enough to provide a convenience yield. These features are not shared by option-implied rates (Ronn and Ronn, 1989, Avino et al., 2017, Geck and Kaserer, 2021, van Binsbergen et al., 2021), which we are the first to compare across countries.

## 2 Near-money assets and convenience yields

We first explain the intuition behind our approach to estimating the convenience yields. Our goal is to compare the yield of a safe, money-like asset to a risk-free rate implied by the prices of assets that are not themselves safe or money-like. Generally, the previous literature has approached this problem by using the yield on a less liquid and/or less safe asset for comparison. However, any sufficiently safe asset can itself have a convenience yield, since it can also a perform a role similar to money. For example, in the original IS-LM model of Hicks (1937) the nominal interest rate measures the return that agents forgo in exchange for holding cash. However, as shown by Krishnamurthy and Vissing-Jorgensen (2012), interest-bearing assets such as Treasuries also earn a convenience yield since they also perform a role similar to money in the financial system. The difference between the yield on two safe, money-like assets therefore only tells us the difference in the two assets' convenience yields.

Following, van Binsbergen, Diamond, and Grotteria (2021), we infer a risk-free rate from assets which are themselves so far from being safe and money-like that they are unlikely to provide a convenience yield. If this risk-free rate has no convenience yield, the spread between it and the interest rate of a safe asset identifies that safe asset's convenience yield. Figure 1 suggests an approach for estimating convenience yields which is valid if an asset's convenience decreases smoothly in the asset's systematic risk before eventually reaching a level of zero for sufficiently risky assets outside of the fixed income market. Assets that provide no convenience have an expected return that is a linear function of the covariance of its payoff's with the stochastic discount factor (SDF). Assets that provide convenience have an expected return strictly lower than the one implied by this linear relationship, with the spread increasing in the safety/convenience of the asset.

Based on this picture, comparing the yield of a Treasury to the yield of a slightly less safe/liquid asset can either overestimate or underestimate the Treasury's convenience yield.

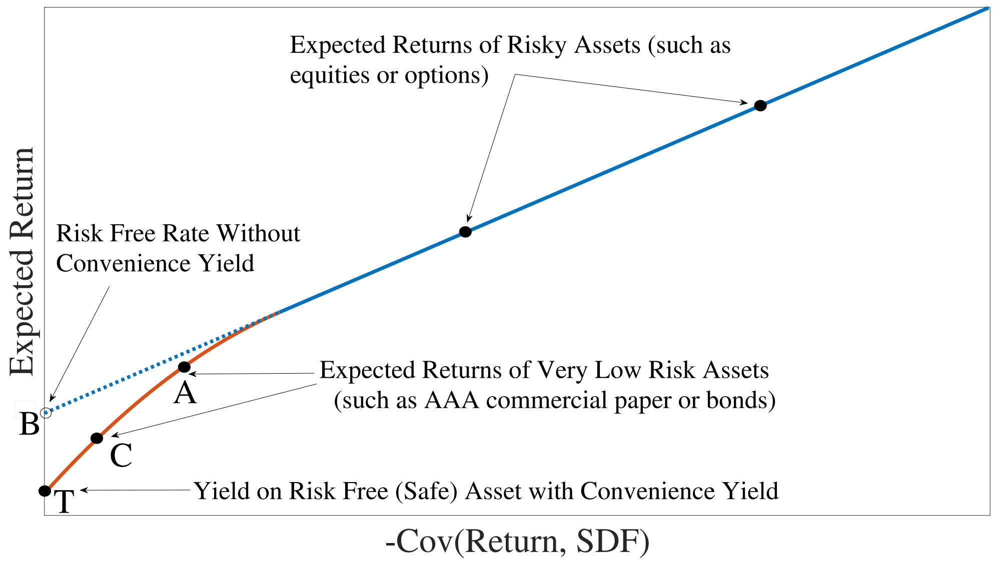


Figure 1. **Risk and return with a special demand for safe assets** Plots the theoretical relationship between an asset's expected return and its covariance with an investor's stochastic discount factor (SDF). Assets with no convenience have an expected return that is a linear function of the covariance with the SDF. Assets that provide convenience have an expected return that is below the typical linear relationship, with a spread that is increasing in the safety/convenience of the asset.

On one hand, very low-risk assets such as the debt of banks or AAA rated companies are somewhat money-like and also provide convenience yields. On the other hand, these low-risk assets need not be perfectly riskless, and the credit risk premium they earn increases their expected return. These two forces combined can result in an expected return above or below the convenience-yield-free risk-free rate (as shown by points C and A in Figure 1). A similar argument applies to OIS rates, since the overnight rate the swap references is likely to have a convenience yield too. This paper attempts to estimate a convenience-yield-free risk-free rate implicit in the prices of risky assets, which should be on the blue line in Figure 1.

## 2.1 Constructing risk-free rates

We infer risk-free rates denominated in each currency using the put-call parity relationship for European options. At time $t$, we observe the prices of a cross-section of options that mature in $T$ periods and have strike prices $K_i$ all denominated in the same currency for $i = 1, ...N$. We aim to infer the interest rate in this currency $r_{t,T}$ on a riskless investment at time $t$ that matures in $T$ implied by these option prices. If we denote the prices at time $t$ of a put and call of strike price $K_i$ that mature in $T$ periods by $p_{i,t,T}$ and $c_{i,t,T}$, the put-call parity relationship can be written as

$$p_{i,t,T} - c_{i,t,T} = (\mathcal{P}_{t,T} - S_t) + \exp(-r_{t,T}T)K_i. \tag{1}$$

In this expression, $S_t$ is the price of the underlying asset on which the options are written and $\mathcal{P}_{t,T}$ is the present value of cash flows paid by the underlying asset before the options mature. The put-call parity relationship for European options follows only from the absence of arbitrage and does not rely on any specific option pricing model.

This put-call parity expression implies that in the absence of arbitrage, there is a perfect linear relationship between the difference $p_{i,t,T} - c_{i,t,T}$ between the prices of puts and calls of strike price $K_i$ and their strike price $K_i$. The slope of this line equals the discount factor $\exp(-r_{t,T}T)$ from which we can infer the interest rate $r_{t,T}$. We therefore can estimate our option-implied interest rates from a cross-sectional linear regression of $p_{i,t,T} - c_{i,t,T}$ on $K_i$. By estimating this regression separately for options whose strike prices are denominated in different currencies, we obtain interest rate estimates for each currency. These rates are risk-free if there is no meaningful counterparty risk in the underlying options, a claim for which we provide evidence in appendix B.

We can write our linear put-call parity expression as

$$p_{i,t,T} - c_{i,t,T} = \alpha_{t,T} + \beta_{t,T} K_i + \varepsilon_{i,t,T}. \tag{2}$$

where an estimate of the slope $\beta_{t,T} = \exp(-r_{t,T}T)$ implies a risk-free rate $r_{t,T}$. Potential deviations from put-call parity are reflected in the error term $\varepsilon_{i,t,T}$, which should be extremely small in a market that is nearly free of arbitrage. We estimate $\beta_{t,T}$ with the OLS estimator

$$\beta_{OLS} = \frac{\sum_i \left((p_{i,t,T} - c_{i,t,T} - \bar{p} - \bar{c})(K_i - \bar{K})\right)}{\sum_i (K_i - \bar{K})^2}, \tag{3}$$

where a bar denotes a variables' sample average. Our implied interest rate estimate is

$$r_{t,T} = -\frac{1}{T} ln(\beta_{OLS}). \tag{4}$$

In addition to providing an interest rate estimate, a measure of fit of this regression (such as its R-squared) provides a useful measure of the size of arbitrage spreads in an option market. Only an R-squared extremely close to 1 provides a precise interest rate estimate.

To estimate our option-implied rates, we use an intraday database of option price quotes from ICE, which we supplement with additional intraday data from the Thompson Reuters Tick Database and finally with daily data from OptionMetrics (see Appendix C for details). We use the midpoint of bid and ask quotes on European options on the most liquid stock index denominated in each of our 10 currencies from which we infer our rates. We show in Appendix B that backing from option clearing houses make our rates effectively free of credit risk and that sophisticated portfolio margin requirements allow investors to lend at our option-implied rates without putting up additional margin beyond the funds they lend.

Figure 2 illustrates our estimation approach. The dots in the figure are the difference between put and call prices of the same strike price and the same one year maturity. To

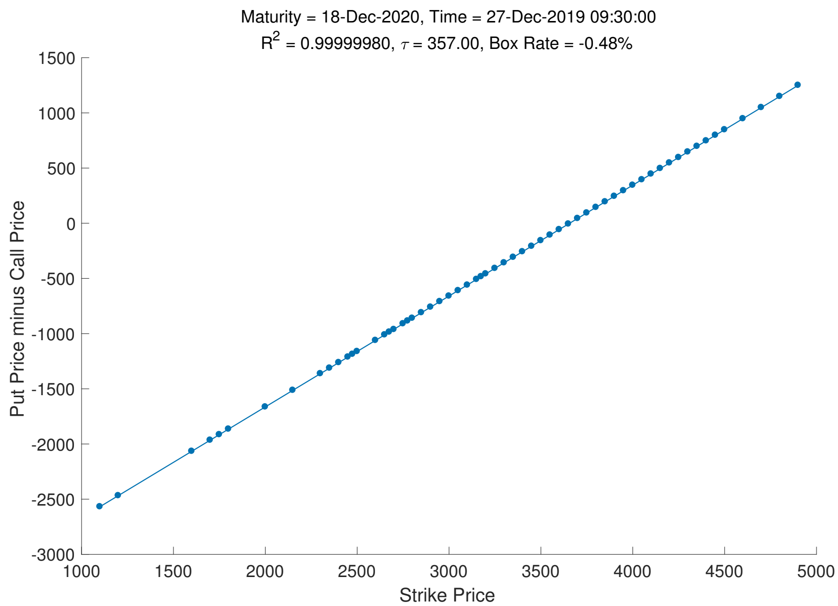


Figure 2. **Box rate estimation from put-call parity** This figure illustrates the linear relationship between put minus call prices and strike prices. Euro Stoxx 50 Index Options (OESX) traded on the EUREX exchange that are denominated in EUR at 9:30am on December 27, 2019 for European options that mature in 357 calendar days on December 18, 2020. The estimate of the option-implied EUR risk-free rate is -.48%.

visual accuracy, the dots live along a line, reflecting the fact that put-call parity holds quite well in our data. A linear regression on this data haans R-squared of .9999998 and an implied interest rate of -48 basis points. To construct our daily time series of interest rates, we run these regressions minute-by-minuteand take a daily median of the resulting estimates. We show in table 1 that the high R-squared of this regression is broadly reflected across countries, though we restrict our analysis to the 4 highest R-squared countries in some analysis. To minimize the impact of outliers, we only use regressions with an R-squared of at least .99999. We linearly interpolate our estimates across the irregularly spaced maturites at which options expire to infer interest rates at a fixed grid of maturities from 3 months to 3 years.

We use the spread between our estimated rate and the interest rate paid by a safe asset to estimate the safe asset's convenience yield. If a zero-coupon safe asset pays a rate $r_{t,T,safe}$

Table 1

Summary Statistics : Average of daily median of R-squared of put-call parity regression in equation 2 used to estimate box rates. For each country, we exclude observations with an R-squared below .99999 and take a median of the remaining regressions within each day. The table then reports the time-series average of this daily median R-squared for each country.

| Country | Stock Index | Mean R-Squared | Days of Data | Start | End |
|---|---|---|---|---|---|
| US | S & P 500 | 0.9999996 | 4781 | 1/2/2004 | 7/1/2020 |
| Europe | STOXX | 0.9999987 | 4587 | 1/2/2004 | 7/27/2020 |
| UK | FTSE 100 | 0.9999982 | 4144 | 1/2/2004 | 7/27/2020 |
| Switzerland | Swiss Market Index | 0.9999979 | 4493 | 1/2/2004 | 7/27/2020 |
| Japan | Nikkei 225 | 0.9999977 | 4098 | 1/6/2005 | 7/27/2020 |
| Canada | TSX 60 | 0.9999972 | 3416 | 1/1/2010 | 3/6/2020 |
| Australia | ASX 200 | 0.9999967 | 4578 | 1/2/2004 | 7/27/2020 |
| Sweden | OMX Stockholm 30 | 0.9999964 | 4184 | 1/3/2005 | 6/30/2020 |
| Norway | OBX 25 | 0.9999943 | 4464 | 1/3/2005 | 7/27/2020 |
| Denmark | OMX Copenhagen 25 | 0.9999941 | 2339 | 1/27/2012 | 6/30/2020 |

from time t to time T and $r_{t,T}$ is our option-implied rate of the same maturity, then our estimate $CY_{t,T,safe}$ of the safe asset's convenience yield is

$$CY_{t,T,safe} = r_{t,T} - r_{t,T,safe}. \tag{5}$$

# 3 Convenience yields around the world

This section reports the average size of our convenience yield estimates with two main results. First, the level of convenience yields in a country is highly correlated with the level of the country's nominal interest rate, with a 1 percent increase in rates predicting a 15 basis point increase in convenience yields. Second, US convenience yields are slightly below the level predicted by its level of interest rates, implying that the dollar's role as a global reserve currency has not given US government debt an unusually large convenience yield.

Table 2 presents the sample averages of our convenience yield estimates across currencies and across maturities. The first panel presents results comparing our box rates to government bond yields while the second compares to shorter maturity bills. All countries have a positive average convenience yield, so every country's government debt pays less than the box rate inferred from options on the country's major stock index. This provides robust evidence that in all countries, a demand for safe, money-like assets pushes government bond yields below the risk free-rates consistent with the pricing of the country's riskier financial assets.

The convenience yield for the US is near the middle of that in other countries. US bonds have an average convenience yield of roughly 35 basis points, with a nearly flat term structure of convenience yields. This is below the convenience yields of four currencies (Australia, Norway, Canada, Sweden) and above that of five (UK, Euro, Switzerland, Japan, Denmark). The highest convenience yields are in Australia (61-63 basis points across maturities), while Switzerland (2-18 basis points across maturities), Japan (11 basis points), and Denmark (15-17 basis points across maturities) have the lowest. Unlike other countries, US bill yields are below the yields of maturity-matched bonds (Lenel et al., 2019, Vanderweyer, 2022).

As shown in Figure 3, the cross-section of average convenience yields across countries is explained well by the average nominal interest rate in each country. Australia and Norway have the highest convenience yields and nominal interest rates, while Denmark, Switzerland, and Japan have low convenience yields and low interest rates. As shown in Table 2, a regression of each country's average one-year convenience yield (with a 6-month maturity used for Sweden, Denmark, and Norway and a 3-month maturity for Japan due to a lack of 1-year maturity data) yields a slope of 15.3 basis points and an R-squared of .74. A 1% increase in interest rates is associated with a 15 basis point convenience yield increase. Our cross-sectional evidence using data across countries complements Nagel (2016), who finds a similar relationship between interest rates and convenience yields in US time-series data.

Table 2. **Summary statistics for government bonds and bills** Average convenience yields, where .01 is a 1 percent yield. Newey-West standard errors based on 100 day lag in parentheses.

| Country | 3 Month | 6 Month | 1 Year | 2 Year | 3 Year |
|---|---|---|---|---|---|
| USA | .0034 (.0003) | .0035 (.0002) | .0035 (.0002) | .0035 (.0003) | |
| UK | .0022 (.0008) | .0030 (.0005) | .0035 (.0003) | .0038 (.0007) | |
| Euro | .0029 (.0004) | .0029 (.0003,4890) | .0027 (.0003) | .0024 (.0002) | .0021 (.0002) |
| Switzerland | | | .0002 (.0002) | .0014 (.0003) | .0018 (.0003) |
| Canada | .0047 (.0009) | .0037 (.0004) | .0036 (.0002) | .0029 (.0002) | |
| Australia | .0061 (.0011) | .0063 (.0010) | .0060 (.0006) | | |
| Country | 3 Month | 6 Month | 1 Year | | |
| USA (Bill) | .0052 (.0003) | .0049 (.0003) | .0048 (.0004) | | |
| UK (Bill) | .0023 (.0005) | .0015 (.0003) | | | |
| Euro (Bill) | | .0035 (.0004) | .0022 (.0003) | | |
| Japan (Bill) | .0011 (.0009) | | | | |
| Norway (Bill) | .0050 (.0004) | .0050 (.0006) | | | |
| Sweden (Bill) | .0037 (.0005) | .0048 (.0006) | | | |
| Switzerland (Bill) | .0025 (.0005) | | | | |
| Canada (Bill) | .0050 (.0009) | .0038 (.0005) | .0036 (.0002) | | |
| Denmark (Bill) | .0017 (.0003) | .0015 (.0006) | | | |

Our data suggests that the relationship between the levels of interest rates and convenience yields breaks down when interest rates become negative. While we have few countries (Denmark, Japan, and Switzerland) that primarily experience negative interest rates, there does not seem to be a positive relationship between interest rates and convenience yields for these very low rate currencies. We provide further evidence for this lack of relationship when rates are negative with an event study in Table 10 and panel data in Table 14. Our theoretical model in section 6 presents an explanation. When rates are positive, the liquidity benefits of cash and other safe assets are closely substitutable. When rates are negative and cash dominates the return on other assets, the cost of holding physical paper cash is not a cost shared by safe, money-like assets that can be traded electronically. Because our paper compares convenience yields across countries, we believe it is the first that shows convenience yields are not related to the level of interest rates once nominal rates become negative.

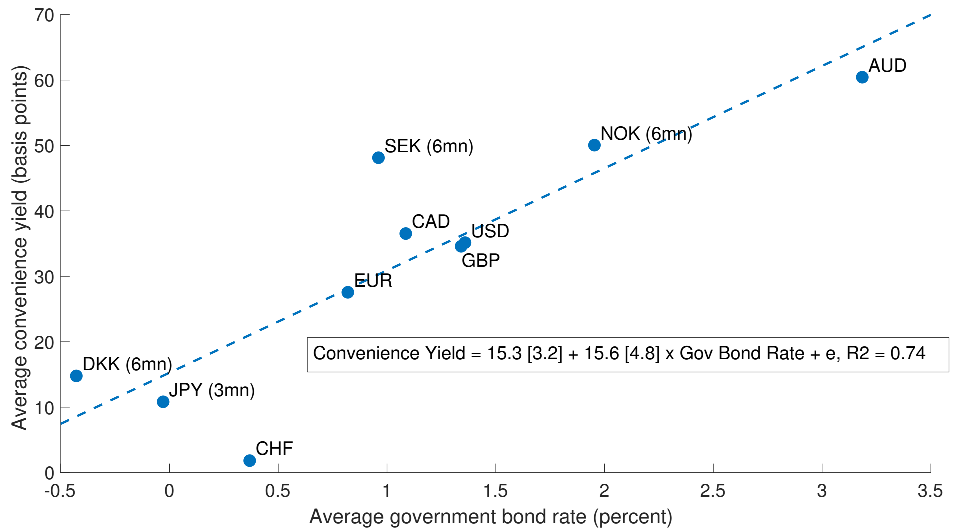


Figure 3. **Cross-section of average convenience yields versus average government bond rates** Plots the average convenience yield against the average government bond rate for each country. The convenience yield is the 1-year box rate minus the 1-year government bond rate in all countries except Norway, Sweden, and Denmark where we use 6-month rates and Japan where we use 3-month rates for a larger sample of observations to estimate average convenience yields.

## 3.1 Cross-section of other risk-free rates and explanatory factors

This section explores how convenience yields on assets other than Treasuries vary with the level of nominal interest rates and other predictors. Table 3 shows that a range of other interest rate spreads than the Box-Treasury spread vary with the level of interest rates. For assets that are more "money-like" than Treasuries, such as savings deposits, the asset's convenience yield increases more than that of Treasuries when interest rates increase. For assets which are less "money-like" than Treasuries, such as corporate bonds, their convenience yield increases less than that of Treasuries. Second, we show in Table 4 that several variables other than nominal interest rates do not explain convenience yield levels across countries.

Table 3 examines how spreads between Treasuries with Box rates, corporate bond yields, interbank borrowing rates (LIBOR), swap rates (OIS), and savings deposit rates vary with the level of interest rates. Our basic hypothesis, following the IS-LM model and Nagel (2016), is that liquidity is more scarce when interest rates are higher, since the nominal interest rate is the income forgone by holding the most liquid asset, cash. As rates increase, liquidity premia should increase proportionately with the nominal interest rate, so the spread between two assets should increase in proportion to the difference in their liquidity/convenience. We find evidence consistent with this hypothesis. A 1% increase in Treasury rates predicts a 63 basis point increase in the convenience yield of savings deposits relative to Box rates. In contrast, the implied convenience yield of risky corporate bonds increases by less than 4 basis points, consistent with corporate bonds being at most slightly more money-like than options.[2] If box rates are the benchmark without a convenience yield, our results imply that OIS and LIBOR rates have convenience yields that are of similar size to Treasury convenience yields.

Table 4 shows that predictors other than the level of nominal interest rates cannot explain the cross-section of countries' convenience yield levels. First, countries with higher sovereign CDS spreads if anything have smaller convenience yields. This shows that the Box-Treasury spread does not measure sovereign default risk, which would require that the spread increase with default risk. Second, a country's government debt-to-GDP ratio has an insignificant ability to predict convenience yields. This differs from Krishnamurthy and Vissing-Jorgensen (2012) who show in US time-series data that a higher debt-to-GDP strongly predicts a lower convenience yield. This suggests that the nominal interest rate, which measures a price of convenience rather than a quantity of safe debt, is the more robust predictor of convenience yields. The R-squared of our put-call parity regression (divided by its cross-sectional standard deviation to normalize), which measures microstructure frictions in option markets, has only a predictive R-squared of .03. Finally the Libor-OIS spread, measuring bank credit risk, and stock market volatility also have minimal predictive power.

[2]This is consistent with Diamond (2020), who presents a model where corporate bonds can back bank deposits but require a buffer of costly equity capital to bear credit risk and therefore are only slightly "money-like."

Table 3. **Cross-country regressions of average interest rate spreads onto average government bond rates** Reports the OLS slope coefficient and explanatory power from a cross-sectional regression of average convenience yields onto average government bond rates for each country using different rates to estimate the convenience yield. For the Box rate we use a 1-year maturity in all countries except Norway, Sweden, and Denmark where we use 6-month rates and Japan where we use 3-month rates for a larger sample size to estimate the average convenience yield. Our corporate yield spreads are from Liao (2020) and aggregate across maturities for AUD, CAD, CHF, EUR, GBP, JPY. For Libor and OIS we use a 1-year spread for USD, GBP, EUR, CHF, a 6-month spread for SEK, DKK, CAD, AUD, and a 3-month spread for JPY. For Libor we use a 6-month spread for NOK and for OIS we exclude NOK because OIS swap rates are unavailable. Savings deposits spreads are computed relative to 3-month bill yields. The final column reports the implied increase in the rate's convenience yield versus the Box rate for a 1% increase in the government bond rate by subtracting its slope coeffients from that for the Box-Treasury spread.

| Rate | Slope (bps) | SE(Slope) | $R^2$ | Number of Countries | Increase vs. Box |
|---|---|---|---|---|---|
| Box | 15.63*** | 3.26 | 0.74 | 10 | 0.00 |
| Corporate | 11.93*** | 4.03 | 0.69 | 6 | 3.70 |
| LIBOR | 4.70 | 6.57 | 0.06 | 10 | 10.92 |
| OIS | -0.05 | 3.89 | 0.00 | 9 | 15.68 |
| Government | | | | | 15.63 |
| Deposit | -47.85*** | 14.58 | .57 | 10 | 63.48 |

Table 4. **Cross-country regressions of average Treasury convenience yields onto different explanatory factors** Each row reports the slope from a cross-sectional OLS regression with an intercept of the average box convenience yield onto the average explanatory factor across countries. The last row reports the number of countries in the regression (N).

| Panel A: Nominal Interest Rates | Slope (bps) | Std. Err. (Slope) | $R^2$ | $\#N$ |
|---|---|---|---|---|
| Government Bond 1y | 15.63*** | 3.26 | 0.74 | 10 |
| Government Bond 2y | 19.04*** | 3.66 | 0.77 | 10 |
| Central Bank Policy Rate | 16.52*** | 3.64 | 0.72 | 10 |
| Libor 3m | 16.63*** | 3.25 | 0.77 | 10 |

| Panel B: Credit Risk and Bond Supply | Slope (bps) | Std. Err. (Slope) | $R^2$ | $N$ |
|---|---|---|---|---|
| CDS 5y | -0.91 | 0.76 | 0.15 | 10 |
| CDS 1y | -1.49 | 1.67 | 0.09 | 10 |
| Debt-to-GDP Ratio | -0.10 | 0.12 | 0.09 | 9 |

| Panel C: Frictions and Volatility | Slope (bps) | Std. Err. (Slope) | $R^2$ | $N$ |
|---|---|---|---|---|
| Normalized Option R-squared | -3.29 | 6.47 | 0.03 | 10 |
| Libor minus OIS spread | -0.49 | 0.41 | 0.16 | 9 |
| Stock market realized volatility | 1.27 | 2.09 | 0.04 | 10 |

# 4 Convenience yields and covered interest parity

This section relates our convenience yield estimates in each country to deviations from covered interest parity (CIP) observed between countries. As documented by Du et al. (2018b), CIP held precisely for interbank borrowing rates (LIBOR) before the 2008 financial crisis but has been persistently been violated since then, largely due to post-crisis financial regulation. CIP deviations between risk-free rates in two currencies can occur for two reasons. First, frictions in international arbitrage can drive a wedge between required rates of return in two countries. Second, the risk-free rates in the two currencies can reflect reflect convenience yields of different size. Using our box rates together with other interest rates, our analysis decomposes CIP deviations into these two distinct channels.

We find that box CIP deviations, which we argue do not reflect a convenience yield, are approximately the same between the US and any foreign country when averaged over time. This is consistent with there being a cost of international arbitrage that is roughly the same size between the US any other G11 country. Unlike our box rate, average CIP deviations constructed from Treasury yields, LIBOR or OIS rates, or savings account rates have magnitudes that strongly vary with the level of countries' nominal interest rates. This is consistent with the hypothesis that these non-box interest rates have convenience yields that vary with the level of nominal interest rates. Our box CIP deviations are therefore a useful candidate measure of the cost of international financial arbitrage. CIP deviations constructed from other rates may reflect both this cost and the difference in countries' convenience yields.

Suppose that one dollar can buy $S_t$ units of foreign currency at time $t$, and promising one dollar in a forward contract in n periods can buy $F_{t,t+n}$ units of foreign currency in n periods. If $i^{\$}_{t,t+n}$ and $i^{f}_{t,t+n}$ are the n-period continuously compounded risk-free rates denominated in dollars and in foreign currency, then covered interest parity holds if

$$exp(ni^{\$}_{t,t+n}) = \frac{S_t}{F_{t,t+n}} exp(ni^{f}_{t,t+n})$$
$$i^{\$}_{t,t+n} = \frac{1}{n}(log(S_t) - log(F_{t,t+n})) + i^{f}_{t,t+n}.$$

CIP reflects the fact that a dollar can be swapped into foreign currency today at exchange rate $S_t$, invested at the foreign rate $i^{f}_{t,t+n}$, and then swapped back to home currency at forward price $F_{t,t+n}$ to construct a "synthetic dollar interest rate." In the absence of arbitrage, this synthetic rate equals the dollar interest rate $i^{\$}_{t,t+n}$. CIP deviations are given by

$$CIPD_{t,t+n} = i^{\$}_{t,t+n} - \frac{1}{n}(log(S_t) - log(F_{t,t+n})) - i^{f}_{t,t+n},$$

which is positive if dollar rates are above synthetic dollar rates and negative if below.

Our analysis of CIP deviations for both box rates and other rates allows us to determine the extent to which CIP deviations are due to a convenience yield for safe assets. Box CIP deviations are an arbitrage spread that does not reference the prices of any safe assets. In contrast, government bond CIP deviations are impacted by the convenience yield of government debt. We decompose the CIP deviation for a risk-free asset $r$ (either a government bond or another safe asset) denominated in dollars \$ and in a foreign currency $f$ as

$$CIPD^{r}_{t,t+n} = i^{\$,r}_{t,t+n} - \frac{1}{n}(log(S_t) - log(F_{t,t+n})) - i^{f,r}_{t,t+n} \tag{6}$$
$$= \left( i^{\$,box}_{t,t+n} - \frac{1}{n}(log(S_t) - log(F_{t,t+n})) - i^{f,box}_{t,t+n} \right) + [(i^{f,box}_{t,t+n} - i^{f,r}_{t,t+n}) - (i^{\$,box}_{t,t+n} - i^{\$,r}_{t,t+n})] \tag{7}$$
$$= CIPD^{box}_{t,t+n} + (CY^{f,r}_{t,t+n} - CY^{\$,r}_{t,t+n}). \tag{8}$$

The box CIP deviation term $CIPD^{box}_{t,t+n}$ is inferred only from the prices of risky assets that should not earn a convenience yield. The second term, $(CY^{f}_{t,t+n} - CY^{\$}_{t,t+n})$ is the difference between our foreign and US convenience yield estimates. Each country's convenience yield is inferred from domestic assets and does not reflect international arbitrage frictions. This decomposition allows us to separate observed CIP deviations into a box CIP deviation, reflecting frictions between countries, and the difference in domestic convenience yields within each country. If discount rates in the US are broadly below foreign ones for identical cash-flows, the box CIP deviation term should be negative. If the convenience yields specifically for US safe assets are larger than in other countries, then the second term should be negative.

We have two main results on the cross-section of CIP deviations. First, every country has a negative box CIP deviation with the dollar, with little heterogeneity in size across countries. Dollar box rates are strictly below synthetic dollar rates implied by any foreign country's box rates. While previous work (Du et al., 2018a,b) shows that most countries have negative CIP deviations with the dollar using other risk-free rates, Australia and New Zealand are exceptions to this. In contrast, our results are consistent with roughly the same cost of international arbitrage between the US and any other G11 country. Our theoretical model in section 6 shows that these results are consistent with dollar funding playing a unique role in the global financial system, with international arbitrageurs paying a cost to borrow risk-free in dollars and lend risk-free in foreign currencies.

Second, the size of a country's box CIP deviation is nearly uncorrelated with the country's level of interest rates. Unlike for box rates, Du et al. (2018a,b) show that the size of CIP deviations using LIBOR,OIS, or government bonds are predicted well by each country's level of interest rates. Our result for box CIP deviations, combined with our previous result that the level of interest rates explains the cross-section of countries' convenience yields, suggests that the variation across countries in the size of CIP deviations found in previous work may be explained by the sizes of safe asset convenience yields across countries.

Tables 5 and 6 present countries' box rate and government bond CIP deviations. In

Table 5. **Summary statistics for average box rate CIP deviations** A deviation of .01 represents a 1 percent yield spread, where the sign convention is that a negative spread reflects that dollar box rates are lower than a rate constructed with foreign box rates and foreign exchange transactions.

| Country | 3 Month | 6 Month | 1 Year | 2 Year |
|---|---|---|---|---|
| Australia | -0.0008 (.0011) | -0.0010 (.0010) | -0.0009 (.0008) | |
| Canada | -0.0019 (.0010) | -0.0012 (.0006) | -0.0011 (.0002) | |
| Switzerland | -0.0008 (.0003) | -0.0011 (.0003) | -0.0014 (.0004) | -0.0020 (.0004) |
| Euro | -0.0004 (.0003) | -0.0005 (.0003) | -0.0008 (.0003) | -0.0012 (.0003) |
| UK | 0.0010 (.0005) | -0.0001 (.0003) | -0.0004 (.0003) | -.0006 (.0008) |
| Japan | -0.0014 (.0014) | | | |
| Norway | -0.0012 (.0005) | -0.0011 (.0006) | | |
| Sweden | -0.0013 (.0005) | -0.0023 (.0006) | | |
| Denmark | -.0008 (.0004) | -.0013 (.0004) | | |

both tables, most CIP deviations are negative, which implies that investors accept a lower rate of return when holding dollar assets than when using the FX market to manufacture synthetic dollar rates from foreign assets. However, box and government CIP deviations behave differently when we examine them across countries. In high-interest rate countries like Australia, government CIP deviations are positive, while in low interest rate countries like Switzerland, Denmark, and Japan, government CIP deviations are the most negative, between -30 and -50 basis points. Figure 4 confirms previous work finding that the size of government CIP deviations is closely related to the level of countries' nominal interest rates.

Unlike CIP deviations for other rates, we find no relationship between a country's interest rate level and the size of its box CIP deviation. Figure 4 shows that the cross-section of box CIP deviation magnitudes is not closely related to the level of interest rates. Table 7 shows that a country's average one-year interest rate has only a slope of 1.6 basis points and an R-squared of .1 for predictiong box CIP deviations. For corporate bond CIP deviations constructed by Liao (2020), which are risky and therefore should earn a minimal convenience yield, there is also almost no relationship with the level of nominal interest rates. This is unlike CIP deviations for government, LIBOR, OIS, and deposit rates. Table 7 shows that a country's average interest rate level predicts the government CIP deviation magnitude with an R-squared of .67, and a 1% rate increase predicts a 12.65 basis point increase in its CIP deviation. For savings deposits, which are even more "money-like" than Treasuries, a 1% rate increase predicts an even larger 49.4 basis point increase in CIP deviations.

Table 6. **Summary statistics for average government bond rate CIP deviations** A deviation of .01 represents a 1 percent yield spread, where the sign convention is that a negative spread reflects that dollar government bond rates are lower than a foreign government bond rate swapped into dollars with a foreign exchange transaction.

| Country | 3 Month | 6 Month | 1 Year | 2 Year |
|---|---|---|---|---|
| Australia | 0.0007 (.0004) | 0.0004 (.0004) | 0.0007 (.0004) | |
| Canada | 0.0002 (.0002) | -0.0003 (.0001) | -0.0006 (.0001) | 0.0001 (.0004) |
| Switzerland | | | -0.0047 (.0004) | -0.0037 (.0005) |
| Euro | -0.0012 (.0002) | -0.0014 (.0002) | -0.0018 (.0003) | -0.0022 (.0005) |
| UK | -0.0019 (.0005) | -0.0013 (.0003) | -0.0006 (.0002) | -0.0001 (.00005) |
| Japan | -0.0032 (.0003) | -0.0036 (.0003) | -0.0044 (.0003) | |
| Norway | -0.0002 (.0003) | -0.0006 (.0004) | | |
| Sweden | -0.0010 (.0005) | -0.0011 (.0004) | | |
| Denmark | -.0020 (.0003) | -.0028 (.0004) | -.0044 (.0003) | |

These results suggest that the unique role of the US in the global financial system is reflected broadly in low dollar-denominated yields and not specifically in low yields for safe assets such as Treasuries. The model in section 6 explains the results by assuming that international arbitrageurs are financed with dollar-denominated debt and face leverage regulation that makes international arbitrage costly. This assumption explains both why box CIP deviations (if box rates have no convenience yield) are negative and of similar magnitude for all countries. In addition, the model has a domestic market for safe assets where convenience yields are proportional to the level of nominal interest rates, with the US no different from other countries. While there may be demand by foreigners to hold US safe assets, this is not reflected narrowly in an unusually large convenience yield for US Treasuries. Instead, international arbitrage frictions result in dollar yields below dollar risk-free rates implicit in foriegn asset prices, even for assets that do not have a convenience yield.

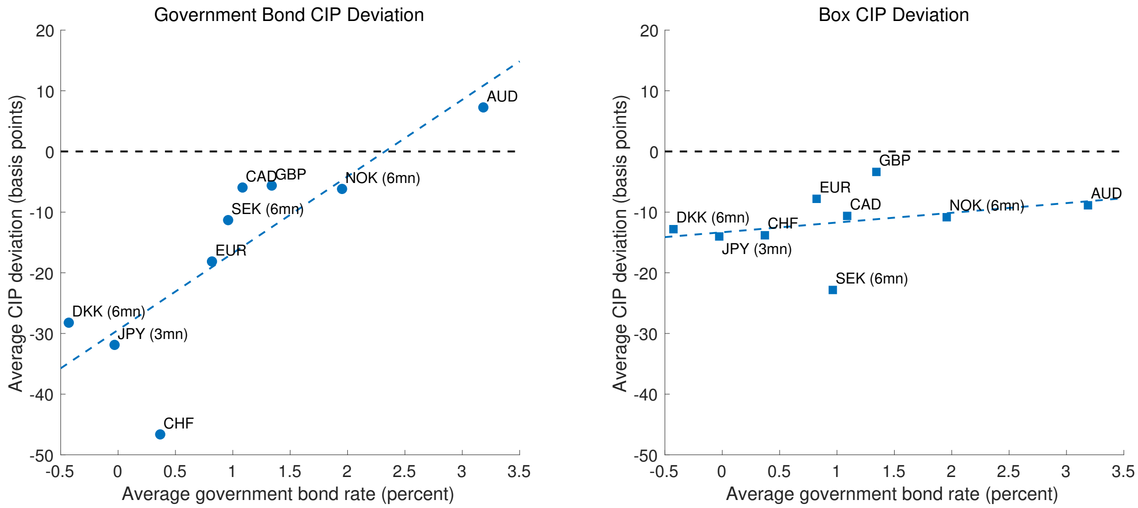


Figure 4. **Cross-section of average CIP deviations for box rates and government bond rates** Plots the average CIP deviation for government bond rates and box rates against the average government bond rate for each country. The CIP deviation is computed for a 1-year maturity in all countries except Norway, Sweden, and Denmark where we use 6-month rates and Japan where we use 3-month rates for a larger sample size of box rates from which we estimate the average CIP deviations.

# 5 Convenience yields and CIP deviations over time

This section examines the behavior of convenience yields over time. We first present a time-series of one year convenience yields in Figure 5 for the four currencies with the most precise rate estimates, the US, UK, Euro, and Switzerland. These convenience yields co-move strongly with each other and seem to rise during identifiable periods of financial distress. For our most precisely estimated currencies, the US and Euro, we present plots of the term structure of their convenience yields in figures 6.

Although the US does not have an unusually large convenience yield, the US-centered 2008 financial crisis had an unusually large impact on convenience yields in other countries. In Figure 5, all countries have by far their largest convenience yields following 2008. The US convenience yield reaches the highest level at roughly 120 basis points, the UK and Switzerland both exceed 100 basis points, and the Euro exceeds 80 basis points.

Table 7. **Cross-country regression of average CIP deviation onto average government bond rate** Reports the OLS slope coefficient and explanatory power from a cross-sectional regression of average CIP deviations onto average government bond rates for each country using different rates to estimate CIP deviations. For the Box rate we use a 1-year maturity in all countries except Norway, Sweden, and Denmark where we use 6-month rates and Japan where we use 3-month rates for a larger sample size. For the corporate rate we use the corporate basis from Liao (2020) which is available for AUD, CAD, CHF, EUR, GBP, and JPY. For Libor and OIS we use a 1-year spread for USD, GBP, EUR, CHF, a 6-month spread for SEK, DKK, CAD, AUD, and a 3-month spread for JPY. For Libor we use a 6-month spread for NOK and for OIS we exclude NOK because OIS swap rates are unavailable. The last column reports the number of countries in the regression ($N$).

| Rate to estimate CIP deviation | Slope (bps) | SE(Slope) | $R^2$ | $N$ |
|---|---|---|---|---|
| Box | 1.60 | 1.77 | 0.10 | 9 |
| Corporate | -1.97 | 2.49 | 0.14 | 6 |
| LIBOR | 12.21*** | 3.44 | 0.64 | 9 |
| OIS | 14.60*** | 2.77 | 0.82 | 8 |
| Government | 12.65*** | 3.32 | 0.67 | 9 |
| Deposit | 49.39 *** | 18.27 | 0.51 | 9 |

The European financial crisis in 2011-2012 lead to a Euro convenience yield over 60 basis points, with only moderate spillovers onto other currencies. In addition, the UK convenience yield exceeds 80 basis points after the March 29, 2017 request to leave the European Union, but convenience yields in other currencies only increase slightly. Swiss convenience yields stay mostly negative starting in late 2010 after Swiss nominal rates also became negative. Swiss convenience yields seem immune to crises in other countries after 2008.

For the currencies in Figure 5, convenience yields tend to spike during financial crises, and a country's own convenience yields spike particularly during a domestic financial crisis. While the 2008 crisis, which originated in the US, was a period where dollar safe assets had a larger convenience yield than other currencies, this is not the case in crises centered in other countries. Euro convenience yields were the largest during the Euro crisis which peaked in 2010-2012, while UK convenience yields were the largest during the Brexit panic of 2017. The difference between US and foreign convenience yields, which by equation 8 contributes to the size of CIP deviations, is not generally larger in financial crises than in other times.

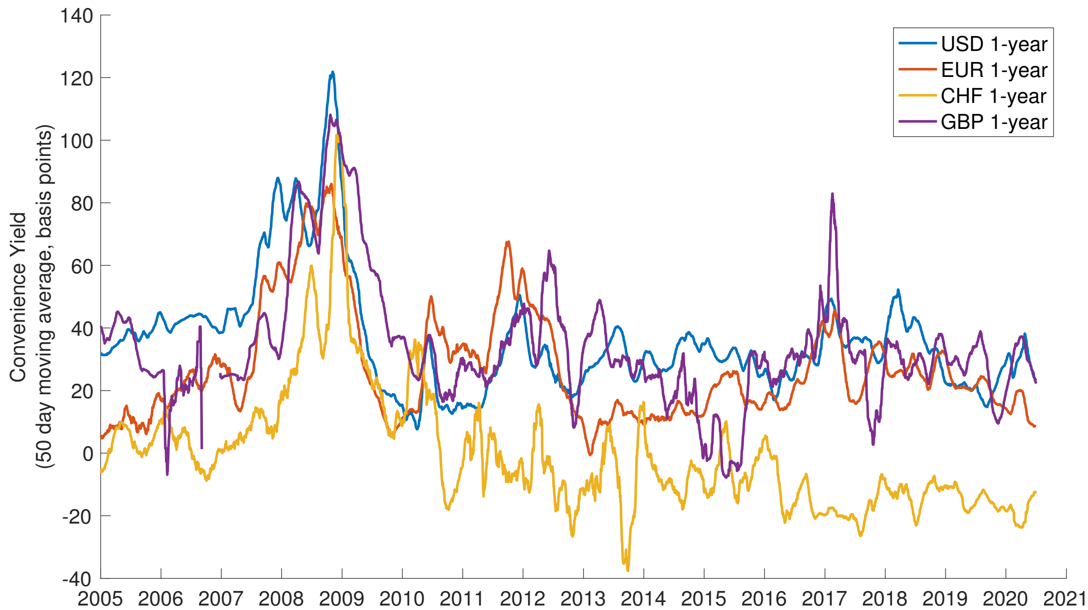


Figure 5. **Time-series of convenience yields for USD, EUR, CHF, GBP** Plots the time-series of box convenience yield estimates for a 1-year maturity for the United States, Europe, Switzerland, and the United Kingdom as a 50-day moving average in basis points.

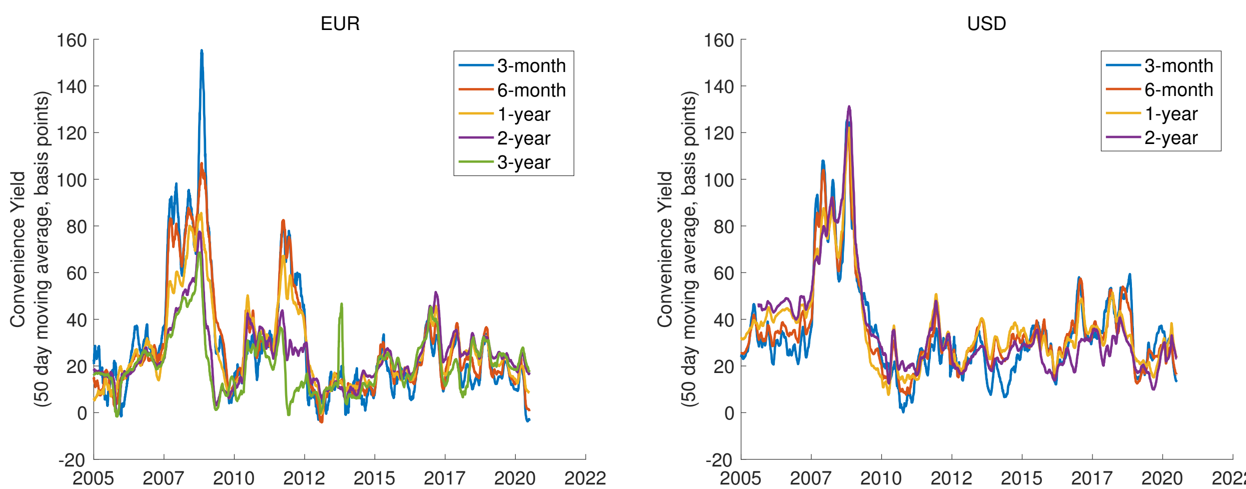


Figure 6. **Term-structure of convenience yields for EUR and USD** Plots the term-structure of box convenience yield estimates for Europe and the United States as a 50-day moving average.

**Term Structure of Convenience Yields** Figure 6 plot the term structure of convenience yields for the two most liquid currencies, the euro and the dollar. In both currencies, there is strong co-movement of convenience yields across maturities, with all maturities increasing in the 2007-2009 US crisis, 2010-2012 Euro crisis, and somewhat in the 2017 Brexit crisis. Smaller convenience yield movements outside of crises also seem to be strongly correlated across maturities in each country. However, the two term structures differ in their conditional slope. In Europe, periods of financial distress feature the highest convenience yields for the shortest maturities, with smaller increases at longer maturities. The term structure of US convenience yields remains roughly flat even when it is elevated.[3]

## 5.1 CIP deviations: Time-series evidence

This section analyzes the time-series behavior of Box and Government CIP deviations. Because the US, Europe, the UK, and Switzerland have the most precisely estimated option-implied interest rates, we restrict ourselves to analyze only these countries. As previous literature has documented (Du et al., 2018a), government CIP deviations grow dramatically during financial crisis such as 2007-2009. By decomposing government CIP deviations into box CIP deviations and convenience yield differences using equation 8, we aim to understand whether a special demand for dollar-denominated safe assets is a key feature of financial crises. We analze two time series: 1. the average one-year box CIP deviation between of the UK, Europe and Switzerland and the US and 2. the difference between the average one-year convenience yield of the UK, Europe and Switzerland and the US one-year convenience yield.

Box CIP deviations become large and negative during financial crises, always moving in the same direction in the crises we observe. This is a key asymmetry in Figure 7, where the

[3] While our box rate maturities goes to a maximum of 3 years, we are unable to analyze patterns in convenience yields at 5-10 year maturities documented in Du et al. (2018a), where US convenience yields seem to decrease over time.

blue line shows dollar rates falling relative to foreign synthetic dollar rates in all observed crises. In the 2007-2009 US financial crisis, the 2011-2012 European financial crisis, and the financial turmoil surrounding Brexit in 2016, US box rates fall below synthetic dollar interest rates constructed using foreign box rates and currency hedging. However, during tranquil periods in financial markets (i.e. when convenience yields are low), synthetic dollar box rates return back near the level of US box rates. This asymmetry is unlike convenience yields themselves, which grow largest in the US during the US crisis, largest in Europe during the Euro crisis, and largest in the UK during the Brexit crisis. The growth in box CIP deviations in all financial crises is one dimension in which the US seems special in the global financial system. Our theoretical model in section 6 is consistent with this finding if international arbitrageurs are exposed to crises in all countries.

Table 8. **Regressions of box CIP deviations and convenience yield differences on government CIP deviations** The first column presents time-series regression results of the average one-year box CIP deviation for the UK Europe and Switzerland on the average one-year government CIP deviation for these same three countries. The second column presents time-series regression results of the difference in the average one-year convenience yield of these 3 countries on the average of their one-year government yield CIP deviations. Observations are at a daily frequency.

| | Box CIP | Conv. Yield Difference |
|---|---|---|
| Intercept | 0.001 ( .00005 ) | -0.001 (.00005) |
| Slope | 0.848 (0.014) | 0.152 (0.014) |
| R-squared | .503 | .0316 |

The difference between US and foreign convenience yields does not seem to grow on average during crises. While this convenience yield difference does increase in 2008 following the bankruptcy of Lehman brothers to roughly 40 basis points, this level that was fairly average before 2008. During the European financial crisis and after Brexit, foreign convenience yields grow more than those in the US. While our sample only has a few crises, this suggests that US convenience yields are only disproportionately large during US-centered financial crises. This is in contrast to box CIP deviations which grow during all financial crises we observe.

Table 8 shows that the increase in government bond CIP deviations in crises is due pri-

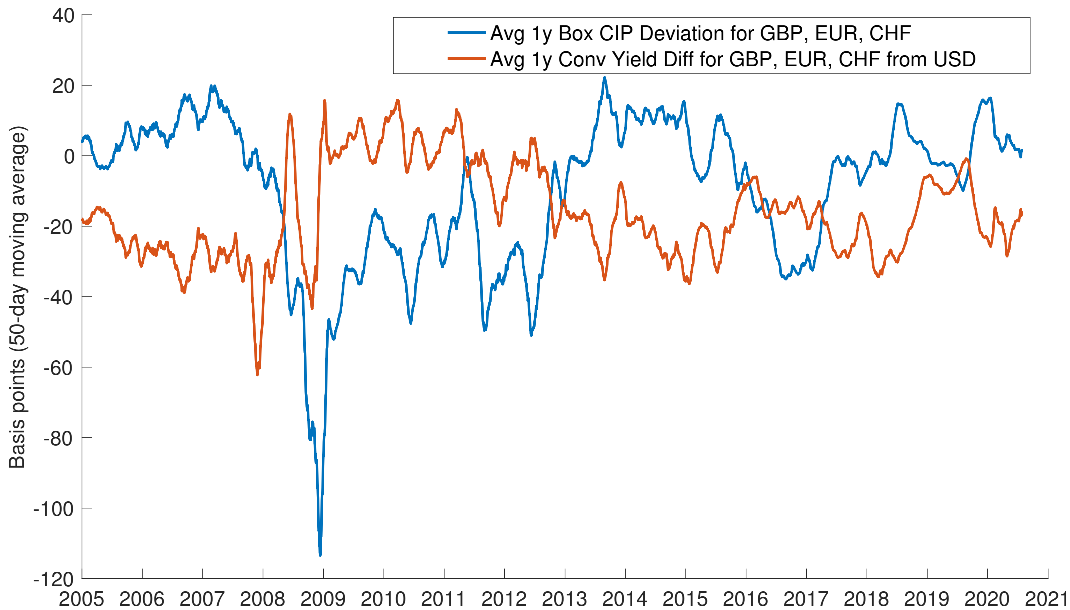


Figure 7. **Average CIP deviation versus average convenience yield difference from the US for GBP, EUR, and CHF** Plots the average 1-year box CIP deviation and 1-year convenience yield difference from the United States for the United Kingdom, Europe, and Switzerland. The CIP deviation and convenience yield difference are averaged across available countries each day and then reported as a 50-day moving average.

marily to international arbitrage frictions that also impact box CIP deviations. A time-series regression of box CIP deviations on government CIP deviations has an R-Squared of .503, while a time-series regression of the difference between US and foreign convenience yields on government CIP deviations has an R-squared of only .316. The time-series correlation between box CIP deviations and convenience yield differences is -.57. Because the sum of these two series equals the government CIP deviation, convenience yield differences tend to reduce rather than amplify the size of government CIP deviations during crises.

## 5.2 Event study: Covid-19 crisis

The March 2020 Covid financial crisis provides additional evidence that box CIP deviations grow during crises, even when dollar convenience yields do not. The brief turmoil in March 2020 is not easily visible in the charts above, since a 50-day moving average nearly removes it. As documented in He et al. (2021), Ma et al. (2021), this crisis featured unusual selling pressure in the US Treasury market, with some long term Treasury rates increasing. At the maturities for which we have box rates, Figure 8 shows that Treasury convenience yields temporarily became negative, consistent Treasuries facing unusual selling pressure.

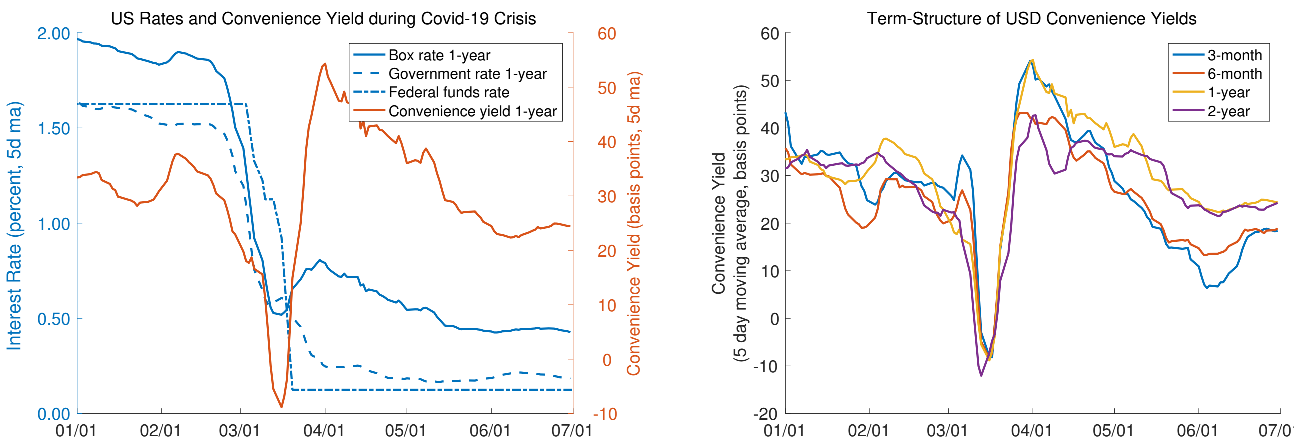


Figure 8. **US short-term rates and convenience yields during the Covid-19 crisis** Left plot shows the 1-year box convenience yield for the United States against the 1-year box rate, 1-year government rate, and midpoint of the Federal funds target range as a five-day moving average from January to June 2020. Right plot reports the term-structure of box convenience yield estimates for the United States as a 5-day moving average from January to June 2020.

However, Figure 9 shows that box CIP deviations behaved similarly in this crisis as in previous ones. Across all three foriegn currencies, synthetic dollar box rates were well above actual dollar box rates, with the difference averaged across maturities peaking near 40 basis points. This is consistent with our previous findings- in all observed financial crises, dollar box rates fall below synthetic dollar box rates. Figure 9 shows that dollar convenience yields

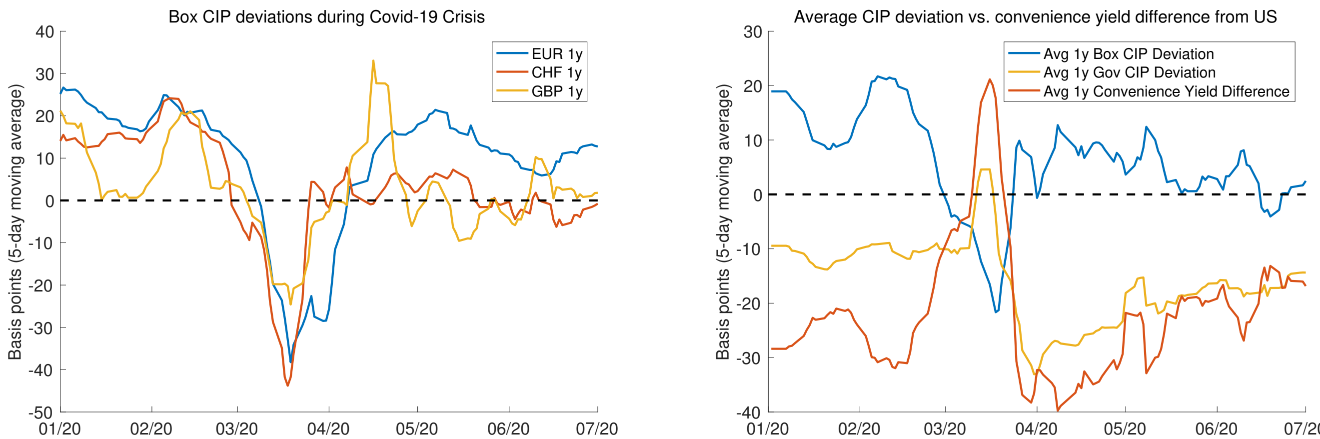


Figure 9. **Box CIP deviations during Covid-19 crisis** Left plot shows the box CIP deviation for Europe, Switzerland, and the United Kingdom averaged across 3, 6, 12, and 24-month maturities from January to June 2020. Right plot shows the average 1-year box rate and government bond rate CIP deviations across Europe, Switzerland, and the United Kingdom against the average convenience yield difference from the United States from January to June 2020.

were lower than foreign ones, suggesting that the turmoil in the US Treasury market was not seen in other countries. Although a negative dollar convenience yield is unusual, the fact that box CIP deviations grew in this crisis but not the difference between US and foreign convenience yields is consistent with larger crises shown in Figure 7. However, the fall in US convenience yields was so large in this crisis that government and box CIP deviations moved in opposite directions in March 2020, as shown in figure Figure 9.

## 5.3 Event study: Central bank policy actions

This section analyzes the impact of central bank policy on convenience yields and CIP deviations. Motivating by the finding in van Binsbergen et al. (2021) that US quantitative easing (QE) only had a large impact during financial crises, we focus on three large policy interventions that occured during periods of unusual stress.[4] We first study the international

[4] Closest to our analysis is Viswanath-Natraj (2020) who considers the impact of QE on CIP deviations without a specific focus on severe crises.

impact of the first round of QE in the US in the 2007-2009 crisis, using the events identified by Krishnamurthy and Vissing-Jorgensen (2011). Next, we consider the impact of QE by the European Central Bank during the European crisis of 2009-2012, using the events identified by Krishnamurthy et al. (2018).[5] Finally, we analyze the event on January 15, 2015 when the Swiss National Bank broke its currency peg with the Euro.

We find that QE policies from both the US and from the ECB reduce domestic as well as foreign convenience yields as well as the magnitude of CIP deviations. We measure the impact of each QE event by taking the difference between the value of target variables a day before after the announcement. We then sum these effects across all of a country's QE announcements to get the overall impact of its policy announcement surprises. Table 9a shows that the Federal Reserve's QE1 policies reduced US convenience yields by 45-61 basis points at various maturities. Both European government and box rates were reduced by these QE announcements, and we find a reduction in European convenience yields at the shortest maturities. Similarly, Table 9b that the ECB's QE policies reduced European convenience yields by 28 basis points at a 6-month maturity, 20 basis points at a 1-year maturity, and had little effect at a 2-year maturity. US convenience yields modestly decreased by 12 basis points at 6-month and 1-year maturities. At 6-month and 1-year maturities, both countries's QE interventions had a positive impact on our box CIP basis. Because box CIP deviations are generally negative, this implies that QE reduced the size of CIP deviations.

These results suggest that during a crisis, QE reduces both domestic and international financial frictions. In our theoretical model, a country's convenience yield during a financial crisis is determined by frictions in its domestic financial system. Because QE reduces convenience yields, this implies that it is reducing the severity of financial frictions. In our model, the size of CIP deviations in a financial crisis is determined by the severity of frictions faced

[5]These dates are November 25th, 2008, December 1st, 2008, December 16th, 2008, January 28th, 2009, and March 18th, 2009 for QE 1 and May 7th, 2009, May 10th, 2010, August 7th, 2011, December 1st, 2011, and July 26th, 2012 for the ECB's QE.

by international financial arbitrageurs. The fact that both US and ECB QE policies reduce CIP deviations therefore suggests that QE reduces frictions in international arbitrage. Our empirical results imply that QE therefore has some ability to reduce both domestic and international financial frictions, although the domestic impact is larger.

Figure 10 and Table 10 show a large fall in Swiss interest rates following the end of the Swiss currency peg with the Euro on January 15, 2015. Rates were relatively stable before and after this event, with a short period of turmoil following it. We therefore use a 2 week event window in Table 9b to study the impact of this event on Swiss interest rates and convenience yields. Across maturities, Swiss Box rates fell from 55 to 116 basis points. We observe a nearly identical impact on government and box rates, so this policy had effectively no impact on Swiss convenience yields. This strengthens our finding that the level of interest rates has little to do with the level of convenience yields when rates are negative.

Table 9. Presents event study evidence on the impact of QE. For each variable, we sum its change from the day before to the day after each QE announcement to get a total change due to all QE announcements. .01 represents a 1 percentage point change in a rate.

| | (a) Impact of Fed QE, Nov 2008-Mar 2009 | | | (b) Impact of ECB QE 2009-2012 | | |
|---|---|---|---|---|---|---|
| Maturity | 6m | 1y | 2y | 6m | 1y | 2y |
| Euro Gov Rate | -0.0025 | -0.0027 | -0.0029 | -0.0014 | -0.0017 | -0.0012 |
| Euro Box Rate | -0.0053 | -0.0057 | -0.0011 | -0.0043 | -0.0037 | -0.0010 |
| Euro Convenience Yield | -0.0028 | -0.0030 | 0.0019 | -0.0028 | -0.0020 | 0.0002 |
| US Gov Rate | -0.0026 | -0.0026 | -0.0036 | 0.0000 | -0.0001 | -0.0002 |
| US Box Rate | -0.0071 | -0.0087 | -0.0096 | -0.0012 | -0.0013 | 0.0003 |
| US Convenience Yield | -0.0045 | -0.0061 | -0.0060 | -0.0012 | -0.0012 | 0.0005 |
| Euro/US Gov CIP | 0.0041 | 0.0047 | 0.0035 | 0.0015 | 0.0008 | -0.0016 |
| Euro/US Box CIP | 0.00244 | 0.00171 | -0.0043 | 0.0032 | 0.0015 | -0.0014 |

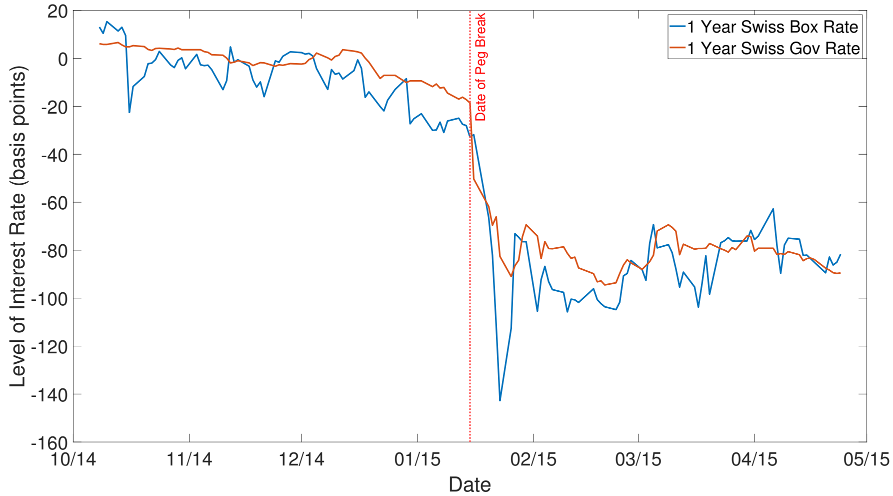


Figure 10. Swiss Interest Rates Before and After End of Euro Currency Peg on Jan 15, 2015

Table 10. Effect of Jan. 15 2015 Break of Swiss Currency Peg on Interest Rates (2-week change), where .01 reprents a 1 percentage point change in rates.

| *Maturity* | 3m | 6m | 1y | 2y | 3y |
|---|---|---|---|---|---|
| Swiss Government Rate | | | -0.0067 | -0.0057 | -0.0053 |
| Swiss Box Rate | -0.0116 | -0.0089 | -0.0071 | -0.0058 | -0.0055 |
| Swiss Convenience Yield | | | -0.0004 | -0.0002 | -.0002 |

## 5.4 Convenience yields, CIP deviations, and exchange rates

This section analyzes the relationship between exchange rates, convenience yields, and box CIP deviations. Both box CIP deviations and the difference between US and foreign convenience yields forecast bilateral exchange rates. This extends Engel and Wu (2022), who forecast exchange rates with government bond CIP deviations, by showing that both convenience yields and international arbitrage frictions explain the predictability they find.

Like Engel and Wu (2022), our benchmark specification is a monthly regression

$$\Delta s_{j,t+1} = \alpha_j + \beta_1 \Delta BoxCIP_{j,t} + \beta_2 BoxCIP_{j,t-1} + \beta_3 \Delta CYdiff_{j,t} + \beta_4 CYdiff_{j,t-1} + u_{j,t+1}, \quad (9)$$

where $\Delta s_{j,t+1}$ is the log exchange rate of currency j with respect the the dollar from month $t$ to month $t+1$, with the convention that it is positive when the dollar appreciates. $BoxCIP_{j,t-1}$ is the country's box CIP deviation with respect to the dollar, with the convention that it is positive when a country's synthetic dollar yield is below the dollar box rate. $CYdiff_{j,t-1}$ is the difference between a country's convenience yield and the dollar's, with the convention that it is positive when a country's convenience yield is larger than the dollar's. We use the exchange rates of the British pound, euro, and Swiss franc against the dollar.

We present our baseline results in the first column of Table 11, and a second predictive regression for the contemporaneous exchange rate change $\Delta s_{j,t}$ in the second column. In both specifications, a 100 basis point reduction in a country's box CIP deviation is associated roughly with a 5% appreciation in its exchange rate. This is consistent with the result that box CIP deviations spike and the dollar appreciates during crises. Similarly, when a country's convenience yield grows 100 basis points larger than that of the dollar, both specifications imply that its exchange appreciates roughly 4 % relative to the dollar. Appendix Table A2 shows that the results are similar when all three currencies are analyzed separately.

Table 11. Monthly Exchange Rate Forecast Regressions, following Engel and Wu (2022). Monthly regression from Jan 2004 to July 2020. Each regression attempts to predict either next month's log exchange rate change $\Delta s_{j,t+1}$ or the contemporaneous exchange rate change $\Delta s_{j,t}$.

| Variable | Coefficient | Standard Error | Coefficient | Standard Error |
|---|---|---|---|---|
| $\Delta BoxCIP_{j,t}$ | - 5.13 | 2.49 | -4.27 | 1.93 |
| $BoxCIP_{j,t-1}$ | -.862 | .852 | -1.79 | .916 |
| $\Delta CYdiff_{j,t}$ | -3.88 | 1.87 | -4.17 | 2.07 |
| $CYdiff_{j,t-1}$ | -.836 | .955 | -1.86 | .953 |
| R-squared: | 0.0531 | | 0.0626 | |
| Predicted varible | $\Delta s_{j,t+1}$ | | $\Delta s_{j,t}$ | |

Next, we examine the ability of exchange rates to predict changes in CIP deviations. This follows Avdjiev et al. (2019), who show that fluctuations of the dollar against a broad basket of other currencies strongly predict LIBOR CIP deviations. Conditional on the return on the so-called "broad dollar", a country's bilateral dollar exchange rate has almost no additional ability to predict its CIP deviation. We find a similar result for box CIP deviations, but the difference between US and foreign convenience yields is nearly uncorrelated with the broad dollar exchange rate. Under the interpretation of Avdjiev et al. (2019) that the broad dollar is a good barometer for global financial frictions, this provides additional evidence that box CIP deviations spike during financial crises but that convenience yield differences do not.

We use changes the US trade-weighted broad dollar index $\Delta Dollar_t$ and changes in country $j$'s bilateral dollar exchange rate $\Delta BER_{jt}$ to predict changes in the variable $x_{jt}$

$$\Delta x_{jt} = \alpha_j + \beta \Delta Dollar_t + \gamma \Delta BER_{jt} + \epsilon_{jt}. \tag{10}$$

We use specification first where $x_{jt}$ is country $j$'s box CIP deviation with the dollar and then where $x_{jt}$ is the difference between the country's convenience yield and that for dollar safe assets. Table 12 shows that this regression has predictive power only for box CIP deviations and not for convenience yield differences. A country's bilateral exchange rate also provides effectively no additional predictive power for box CIP deviations once the broad dollar index is included. Our results imply that a one percentage point increase in the broad dollar is associated with a 1.72 basis point increase in the size of the one-year box CIP deviation, between the 2.6 bps and 1.1 bps Avdjiev et al. (2019) respectively reports at a 3-month and 5-year maturity. Relative to existing work, our contribution is to show that this predictability is due to international arbitrage frictions measured by box CIP deviations and not to differences between countries' convenience yields.

Table 12. Panel A: Prediction of Box CIP deviation (in basis points) using bilateral exchange rate and broad dollar exchange rate. Monthly regression from Jan 2004 to July 2020 using data from the UK, Europe, and Switzerland relative to the US. Panel B: Prediction of convenience yield differences (in basis points) using bilateral exchange rate and broad dollar exchange rate. Monthly regression from Jan 2004 to July 2020 using data from the UK, Europe, and Switzerland relative to the US.

| Panel A: | | |
|---|---|---|
| $\Delta BER_{jt}$ | .229 (.35) | -.47 (.23 ) |
| $\Delta Dollar_t$ | -1.72 (.56) | |
| R-squared | 0.027 | 0.007 |

| Panel B: | | |
|---|---|---|
| $\Delta BER_{jt}$ | -.27 (.54 ) | -.22 (.22 ) |
| $\Delta Dollar_t$ | -.15 ( .34 ) | |
| R-squared | 0.003 | .002 |

## 5.5 Convenience yields, CIP deviations, and interest rates

This section analyzes the ability of a country's nominal interest rates to predict the size its convenience yields and its CIP deviations in panel data. The predictability of convenience yields is related to Nagel (2016), who shows that his convenience yield measure can be predicted well in US data with nominal interest rates. Like Nagel, we control for the S&P 500 VIX as a measure of financial crises, when convenience yields grow and interest rates fall. Column (1)-(3) of table 13 show that a 1% increase in the US federal funds rate is associated with a 5.6 basis point convenience yield increase, close to the 6.5 bps found by Nagel, with similar results for the Euro and Swiss Franc. Columns (4-6) presents panel regressions in all ten countries with even stronger results.[6] With time fixed effects, which are a better control than the VIX for financial crises, we see a 14 basis point convenience yield increase resulting from a 1% interest rate increase, close to the 15 basis point result in Table 2.

Table 14 strengthens the evidence from Figure 3 that interest rates lose their ability to predict convenience yields when they are negative. We run the same panel regression on subsamples with positive and negative nominal interest rates. The within R-squared of predicting convenience yields with nominal interest rates falls to .01 when rates are negative,

[6] Appendix Figure A1 plots the monthly average box rate for each currency that is used in the panel regression analysis.

Table 13. **Convenience yield panel regressions** Monthly panel regression of the convenience yield onto the central bank policy rate and the VIX. Central bank policy rate for short-term nominal interest rates and the VIX index are averaged each month. The convenience yield is the 1-year box rate minus the 1-year government bond rate for all countries except SEK, DKK, and NOK where we use 6-month rates and JPY where we use 3-month rates. For a currency-month observation to be included in the sample we require at least five days of observed box rates to compute the average monthly convenience yield. The sample period is January 2004 to June 2020.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Central Bank Policy Rate | 5.61*** | 6.38** | 9.44*** | 8.77*** | 14.34*** | 5.80*** |
| | (1.40) | (2.71) | (1.97) | (1.29) | (1.83) | (0.90) |
| VIX | 1.17*** | 0.92*** | 1.06** | 1.10*** | | 1.14*** |
| | (0.42) | (0.24) | (0.41) | (0.25) | | (0.21) |
| R-squared adjusted | .423 | .422 | .496 | .247 | .326 | .469 |
| Within R-squared | | | | | .225 | .218 |
| Currency | USD | EUR | CHF | All | All | All |
| Fixed Effects | None | None | None | None | Time | Currency |
| Observations | 198 | 198 | 198 | 1330 | 1330 | 1330 |

Notes: HAC standard errors (12 lags) in parentheses, * $p < .10$, ** $p < .05$, *** $p < .01$

with each country's convenience yield predicted well by a fixed effect for that country. This is consistent with our theoretical result in equation 15 that nominal interest rates are no longer a sufficient statistic for the level of convenience yields when interest rates are negative.

Table 14. **Convenience yield panel regressions for positive versus negative interest rates** Monthly panel regression of the convenience yield onto the central bank policy rate and the VIX. Column (1) estimates the regression on the subsample with non-negative policy rates. Column (2) estimates the regression on the subsample with negative policy rates. The sample period is January 2004 to June 2020.

| | (1) | (2) |
|---|---|---|
| Central Bank Policy Rate | 5.06*** | 5.49 |
| | (0.92) | (9.15) |
| VIX | 1.25*** | 0.15 |
| | (0.21) | (0.17) |
| R-squared adjusted | .45 | .622 |
| Within R-squared | .204 | .01 |
| Currency | All | All |
| Fixed Effects | Currency | Currency |
| Policy Rate | Non-Negative | Negative |
| Observations | 1035 | 295 |

Notes: HAC standard errors (12 lags) in parentheses,
* $p < .10$, ** $p < .05$, *** $p < .01$

Finally, we examine in table 15 the ability of nominal interest rates to predict CIP deviations in panel data. We follow our strongest result from table 13 and include time fixed effects to control for periods of crisis. For government, LIBOR and OIS CIP deviations, which we argue in table 3 are likely to feature convenience yields, nominal interest rates are a significant predictor. For box or corporate bond CIP deviations that we argue have little or no convenience yield, interest rates have almost no predictive power, as seen in the low within-R-squareds in columns (3) and (5). Like our cross-sectional evidence, this is consistent with the dispersion in CIP deviations across countries being due to differences in countries' convenience yields. Once these convenience yields are removed, CIP deviations are consistent with the same cost of arbitrage between the US and any other G11 country.

Table 15. **CIP panel regressions** Monthly panel regression of the CIP deviations onto the central bank policy rate. CIP deviations are computed at a 1-year matuirity except SEK, DKK, and NOK where we use 6-month rates and JPY where we use 3-month rates. Corporate CIP deviations are from Liao (2020) and do not have a specific maturity. For a currency-month observation to be included in the sample we require at least five days of observed rates to compute the average monthly CIP deviation.

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Central Bank Policy Rate | 15.55*** | 6.08*** | -1.30 | 10.16*** | 0.22 |
| | (2.16) | (2.01) | (1.25) | (2.22) | (0.86) |
| R-squared adjusted | .474 | .31 | .32 | .489 | .289 |
| Within R-squared | .328 | .085 | .003 | .205 | .001 |
| Currencies | All | All | All | 8 | 6 |
| Interest Rate | Government | LIBOR | Box | OIS | Corporate |
| Observations | 1132 | 1152 | 1152 | 986 | 617 |

Notes: HAC standard errors (12 lags) in parentheses,
* $p < .10$, ** $p < .05$, *** $p < .01$

# 6 Theoretical explanation

This section presents a simple theoretical model somewhat related to that of Nagel (2016) that can rationalize four of our main findings. First, a country's average convenience yield increases linearly in the level of nominal interest rates, except when interest rates become negative. Second, convenience yields in each country spike when the country's domestic financial system experiences a crisis. Third, CIP deviations for risk-free rates which do not provide a convenience yield are the same magnitude across all countries and spike during any international financial crisis. Fourth, for assets which do earn a convenience yield, CIP deviations vary across countries with the level of nominal interest rates.

**Consumer** The model has 3 periods t=0,1,2, with consumers only active at $t = 0, 2$. In each country j, asset k pays a real cash flow $\delta_{jk}$, denominated in units of the local consumption good at time 2. In addition, there are two "special assets" demanded by consumers- deposits and cash. Deposits and cash provide liquidity services to consumers that appear directly in their utility function. Deposits pay a risk-free nominal interest rate $i_{jd,0}$ while cash pays no interest. Country $j$'s consumer is endowed with initial wealth $W_j$ and maximizes its utility

$$u(c_{j0}) + \beta E_0 u(c_{j2}) + v(C_{j0}, D_{j0}) \tag{11}$$

where $C_{j0}$ and $D_{j0}$ are respectively real cash and deposit holdings(nominal holdings divided by the current price level $P_{j0}$). To capture the idea that depositors are inattentive and slow-moving, deposits issued at time 0 are only redeemed at time 2. At time 1, deposits and deposit rates are held fixed. We impose the functional form

$$v(C_{j0}, D_{j0}) = F(min(C_{j0}, C^*) + \kappa D_{j0}) - G(max(C_{j0} - C^*, 0)) \tag{12}$$

on the consumer's benefits of holding liquid assets, where $F$ and $G$ are strictly increasing functions with $F'' < 0$ and $G'' > 0$ and $0 > \kappa > 1$ is a constant. Up to a satiation point $C^*$, cash provides liquidity benefits that are pefectly substitutable for deposits. Becuase $\kappa < 1$, cash is strictly more liquid than deposits, so deposits can pay interest even when cash does not. Beyond the satiation point $C^*$, cash no longer provides liquidity benefits, and the cost function G reflects fact that it is a physical piece of paper that is costly to store. This cost stops consumers from substituting entirely to cash when interest rates are negative. Because G is additively seperable from F, the storage cost of cash is not shared by bank deposits.

We show in appendix A.1 that the deposit spread is

$$i_{j0} - i_{jd,0} = i_{j0} \frac{\frac{\partial v(C_{j0}, D_{j0})}{\partial D_{j0}}}{\frac{\partial v(C_{j0}, D_{j0})}{\partial C_{j0}}}, \tag{13}$$

where $i_{j0}$ is the nominal risk-free rate from for an asset that provides no liquidity services.

When the nominal interest rate is positive, cash must provide a positive liquidity benefit so $C_{jt} < C^*$. In this case, $\frac{\frac{\partial v(C_{j0}, D_{j0})}{\partial D_{j0}}}{\frac{\partial v(C_{j0}, D_{j0})}{\partial C_{j0}}} = \kappa$ and we get a positive linear relationship between nominal interest rates and the deposit convenience yield

$$i_{j0} - i_{jd,0} = i_{j0}\kappa. \tag{14}$$

When the nominal interest rate is negative, we must have that $C_{j0} > C^*$, which implies that

$$\frac{\partial v(C_{j0}, D_{j0})}{\partial C_{j0}} = -G'(C_{j0} - C^*), \qquad \frac{\partial v(C_{j0}, D_{j0})}{\partial D_{j0}} = F'(C^* + \kappa D_{j0})\kappa. \tag{15}$$

In this case, the liquidity benefit of holding deposits is not impacted by the supply of cash. When nominal interest rates are negative, the (negative) liquidity benefit of holding cash depends only on the quantity of cash held. Likewise, the real convenience yield for deposits depends only on the quantity of deposits held and is unrelated to the level of nominal interest rates. We summarize our results in the following proposition (with details in the appendix).

PROPOSITION 1 The convenience yield $i_{j0} - i_{jd,0}$ of bank deposits increases linearly with the level of nominal interest rates $i_{j0}$ when rates are above 0. When rates are negative, real deposit convenience yields are unaffected by policy that lowers nominal interest rates.

**Supply of deposits from intermediary** The deposits held by consumers are produced by financial intermediaries. In each country j, an intermediary is active in all 3 periods t=0,1,2. It issues equity and deposits at time 0, raises additional equity financing at time

1 with a frictional cost $C(e_{j1})$, and then pays cash flows $\delta^I_{j2}$ at time 2. Funds it raises at time 1 are taken from the consumer at time 0. It maximizes the value of its equity, which is priced by the consumption Euler equation (appendix equation A3). Its objective function is

$$-[e_{j0}] - E_0[e_{j1} + C(e_{j1})] + \beta E_0 \frac{u'(c_{j2})}{u'(c_{j0})} \delta^I_{j2}. \tag{16}$$

The intermediary picks a portfolio with portfolio weights $w^{I,0}_{jk}$ at time 0 and can rebalance to a new portofolio $w^{I,1}_{jk}$ at time 1. The intermediary faces a capital constraint that caps its deposit issuance. The constraint takes a general form $f(w^{I,1}_{jk}) \geq D_{j0}$ for some function $f$ of the vector $w^{I,1}_{jk}$. We set $f(w_{jk}) = \frac{\sum_k (1-(\lambda+\lambda^*_k)) w^{I,1}_{jk} \delta_{jk}}{(1+i_{jd,0}) \frac{P_{j0}}{P_{j2}}}$, so the constraint becomes

$$\sum_k (1 - (\lambda + \lambda^*_k)) w^{I,1}_{jk} \delta_{jk} \geq (1 + i_{jd,0}) D_{j0} \frac{P_{j0}}{P_{j2}}. \tag{17}$$

This constraint can be interpreted as a risk or liquidity weighted capital requirement. The right hand side of inequality 17 is the real value at time 2 of deposits issued at time 0, which compound at the real interest rate $(1+i_{jd,0})\frac{P_{j0}}{P_{j2}}$. The left hand side has a weighted sum of the real payoffs of the intermediary's portfolio at time 2 with weights $(1-(\lambda+\lambda^*_k)) < 1$. For most assets, we think of $\lambda^*_k = 0$, but some special/convenient safe assets such as Treasuries receive preferential regulatory treatment, $\lambda^*_k < 0$. Holding a Treasury allows the intermediary to issue more deposits than by holding other assets with $\lambda^*_k = 0$ that provide the same payoff. Inequality 17 bounds the intermediary's leverage in every state of the world.

At time 0, risk-free asset k's convenience yield is the spread between its interest rate $i_{jk,0}$ and the risk-free rate $i_{j0}$ of an asset that backs no deposits, which by Appendix A.2 equals

$$i_{j0} - i_{jk,0} = \frac{\partial f}{\partial w_{jk}} (i_{j0} - i_{jd,0}). \tag{18}$$

The convenience yield on an asset the intermediary buys is the amount of deposits $\frac{\partial f}{\partial w_{jk}}$ it backs times the deposit convenience yield $i_{j0} - i_{jd,0}$. Using inequality 17, this becomes

$$i_{j0} - i_{jk,0} = \frac{1 + i_{jk,0}}{1 + i_{jd,0}} (1 - (\lambda + \lambda_k^*))(i_{j0} - i_{jd,0}). \tag{19}$$

Deposit convenience yields (which come from households' liquidity preferences) impact the convenience yields on assets held by the intermediary, because buying these assets allows the intermediary to issue deposits. When nominal interest rates are positive, this implies that the nominal interest rate determines the convenience yield of assets owned by the intermediary too. One empirical implication of equation 18 is that if deposit convenience yields $(i_{j0} - i_{jd,0})$ increase with with slope $\kappa$ as rates rise, the convenience yield of asset k increases with slope $\frac{\partial f}{\partial w_{jk}} \kappa$. This is consistent Table 3, showing that convenience yields for less money-like assets vary less with the level of interest rates. We summarize this result below.

Proposition 2 If the intermediary can issue $\frac{\partial f}{\partial w_{jk}}$ deposits by buying one unit of asset $k$, the convenience yield on this asset is equal to $\frac{\partial f}{\partial w_{jk}}$ times the convenience yield on deposits. If deposit convenience yields increase linearly with slope $\kappa$ with the level of nominal rates, the convenience yield of asset k increases with slope $\frac{\partial f}{\partial w_{jk}} \kappa$, so assets which provide less convenience $\frac{\partial f}{\partial w_{jk}}$ have convenience yields that vary less with the level of interest rates.

Next, we analyize the intermediary's decisions at time 1. At time 1, the intermediary can rebalance its portfolio but cannot change its quantity of deposits issued. In period 1, the intermediary can choose to issue additional equity needed to meet its capital constraint. It can use this new equity to make risk-free loans to the household until it has sufficiently many assets. Appendix A.2 shows that to a first-order approximation the convenience yield $i_{j,1} - i_{jk,1}$ on asset $k$ is given by

$$i_{j,1} - i_{jk,1} \approx \frac{C'(e_{j1})}{1 + C'(e_{j1})} \beta(E_1 u'(c_{j2})) \frac{(1 - (\lambda + \lambda_k^*))}{1 - \lambda} min_1 \frac{P_{j0}}{P_{j2}}. \tag{20}$$

As a result, convenience yields increase when the cost $C'(e_{j1})$ of raising equity or the marginal utility $E_1 u'(c_{j2})$ of the intermediary's equityholders increase. An asset's convenience yield also depends on the ratio $\frac{(1-(\lambda+\lambda_k^*))}{1-\lambda}$ between the quantity of $(1-(\lambda+\lambda_k^*))$ deposits it can back versus a "non-special" asset with weight $\lambda$. Finally, the expression $min_1 \frac{P_{j0}}{P_{j2}}$ is smallest posible ratio between time 0 and 2 prices given time 1 information. Equation 20 explains why convenience yields spike during financial crises when cost of raising equity and investor risk aversion are high. However, the ex ante expectation of time 1 convenience yields is related to deposit convenience yields. Appendix A.2 shows that after a Taylor approximation

$$i_{j,0} - i_{jk,0} \approx E_0(1 + C'(e_{j1}))[i_{j,1} - i_{jk,1}]. \tag{21}$$

The time 0 convenience yield of asset k approximately equals a weighted expectation of its time 1 convenience yield, where the weight is the marginal cost $(1+C'(e_{j1}))$ of equity issuance. Our model therefore is jointly consistent with two key facts about convenience yields. First, the average level of convenience yields on all safe assets in a country are determined by the level of nominal interest rates, since this is what determines the convenience yield of deposits. Second, convenience yields spike during periods of financial distress when intermediaries are constrained. The following proposition summarizes our results.

Proposition 3 At time 1, the convenience yield $i_{j,1} - i_{jk,1}$ increases with the marginal cost $C'(e_{j1})$ of intermediary equity. To a first order approximation, the time zero convenience yield $i_{j,0} - i_{jk,0}$ of asset $k$ equals the weighted expectation $E_0(1 + C'(e_{j1}))[i_{j,1} - i_{jk,1}]$, so time 1 convenience yields are expected to be larger for countries with larger time 0 convenience yields and with higher expected costs $C'(e_{j1})$ of intermediary equity.

**International Financial Arbitrage** In addition to the domestic financial intermediary, there is an international arbitrageur such as a hedge fund or dealer bank that trades across countries. It is not funded by deposits but by a mix of equity and risk-free wholesale dollar funding. This is consistent with Anderson et al. (2020) showing that international arbitrage is financed primarily with wholesale funding rather than retail bank deposits and that the global shadow banking system relies on dollar funding. The fact that arbitraguer debt is dollar-denominated is the only difference between the dollar and other currencies in the model. Arbitrageur debt is a non-special asset with $\lambda_k = 0$, and special assets in other currencies do not provide it any convenience. While the arbitrageur's debt must be dollar-denominated, its equity is held by the consumers in a country $J$ that need not be the US.

The arbitrageur maximizes shareholder value with the objective function

$$-[e_{F0}] - E[e_{F1} + C(e_{F1})] + \beta E \frac{u'(c_{J2})}{u'(c_{J0})}[\delta_2^F]. \tag{22}$$

It can borrow from the US intermediary at rates $i_{F,0}$ at time 0 and $i_{F,1}$ at time 1 and repays its loans at time 2. It faces a constraint that its leverage ratio cannot be greater than a constant $L_r$ in any state of the world. Let $i_{\$,t}$ be the dollar risk-free rate the arbitrageur would accept on an asset that does not loosen its leverage constraint, so

$$\frac{1}{1+i_{\$,0}} = \beta E_0 \frac{u'(c_{J2})}{u'(c_{J0})} \frac{e_{\$J,2}}{e_{\$J,0}} \frac{P_{j0}}{P_{j2}} \tag{23}$$

$$\frac{1}{1+i_{\$,1}} = \beta E_1 \frac{u'(c_{J2})}{u'(c_{J0})} \frac{e_{\$J,2}}{e_{\$J,0}(1+C'(e_{F1}))} \frac{P_{j0}}{P_{j2}}. \tag{24}$$

For any risk free-dollar denominated asset $k$ held by the arbitrageur, appendix A.3 shows that its interest rates $i_{\$k,0}, i_{\$k,1}$ at times 0 and 1 satisfy

$$i_{\$k,0} - i_{F,0} = \frac{1+i_{\$k,0}}{1+i_{\$,0}}(1-L_r)(i_{\$,0} - i_{F,0}) \tag{25}$$

$$i_{\$k,1} - i_{F,1} = \frac{1+i_{\$k,1}}{1+i_{\$,1}}(1-L_r)(i_{\$,1} - i_{F,1}). \tag{26}$$

These expressions are the spread between the dollar-denominated rate $i_{F,t}$ at which the arbitrageur borrows and $i_{\$k,t}$ at which it lends, such as by holding synthetic dollar assets in non-US countries. The spreads can therefore be interpreted as CIP deviations. First, note that these CIP deviations do not depend on the identity of the asset k. This is consistent with box CIP deviations being approximately the same on average across countries. Second, the time one CIP deviation spikes when the spread $(i_{\$,1} - i_{F,1})$ increases. The borrowing rate $i_{F,1}$ is a function only of the rate at which the US domestic financial intermediary lends. However, the rate $i_{\$,1}$ increases when the marginal cost $C'(e_{F1})$ of arbitrageur equity increases. As a result, the time 1 CIP deviation increases whenever the intermediary becomes more financially constrained. This explains the asymmetry in the data that box CIP deviations spike in the same direction during all financial crises, regardless of whether they are centered in the US. The key asymmetry in the model is that international arbitrageurs are funded with dollar debt and buy synthetic dollar assets. When the arbitrageur's financial constraints tighten, the borrowing and lending rates of the arbitrageur diverge, resulting in larger CIP deviations. We summarize these results in the following proposition.

PROPOSITION 4 Synthetic dollar assets held by the arbitrageur have yields strictly higher than the dollar rate at which it can borrow, implying that CIP is violated. The size of this CIP deviation is the same across countries. An increase in the cost at time 1 $C'(e_{F1})$ of arbitrageur equity increases the magnitude of CIP deviations.

If we map our box rates onto "non-convenient" assets held by the arbitrageur, the model explains both why box CIP deviations are the same size across countries and why these CIP deviations spike during crises. In addition, the model can explain the fact that CIP deviations vary with the level of nominal interest rates for more covenient assets, since convenience yields grow with interest rates. For an convenient asset $k$ in country $j$ for which $\lambda_k^* < 0$, as noted in equation 8, its CIP deviation can be written as the sum of the box CIP deviation and the difference between its convenience yield in country j and its convenience yield in the US. This matches our results in Table 7 that CIP deviations constructed from more money-like assets vary more with the level of nominal interest rates.

# 7 Conclusion

This paper infers risk-free rates from index option prices to estimate the convenience yields of safe assets in 10 of the G11 currencies. A country's average convenience yield increases 15 basis points with a 1% rise in nominal interest rates, although this relationship breaks down with negative nominal interest rates. The average US Treasury convenience yield is 35 basis points, slightly below that predicted by its interest rate level. Box CIP deviations are roughly the same average size of 10 basis points between the US and any G11 country, with this spread spiking during crises. In constrast, CIP deviations constructed from assets that earn a convenience yield vary strongly with the level of countries' nominal interest rates. CIP deviations and convenience yields both spike across the world during financial crises, but US convenience yields do not grow more than those of other countries.

Previous research has interpreted the growth of CIP deviations and US convenience yields during crises as evidence of a particularly large convenience yield for dollar safe assets. Using our box rates, which we argue do not have a convenience yield, we provide two key facts that suggest a new interpetation. First, foreign convenience yields are just as large and just as sensitive to crises as US ones. Second, box CIP deviations are nearly the same size between the US and any other G11 country. To explain our new facts and existing ones, we propose a model where an international financial system funded with dollar-denominated debt, rather than an unusually large US convenience yield, makes the dollar unique in global finance.

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# Appendix

# A Model Derivations

## A.1 Consumer's Problem

The representative consumer in county j is endowed with wealth $W_j$ and maximizes their utility

$$u(c_{j0}) + \beta E_0 u(c_{j2}) + v(C_{j0}, D_{j0}) \tag{A1}$$

where C is real cash holdings and D is real deposit holdings (that is, nominal holdings divided by the current price level $P_{jt}$) and $c_{jt}$ is consumption in country j at time t. Their consumption at time 0 is $c_{j1} = W_j - C_{jt} - D_{jt} - \sum_k w_{jk} p_{jk}$. Their consumption at time 2 is $c_{j2} = \frac{P_{j0}}{P_{j,2}}[C_{jt} + (1 + i_{jd,0})D_{jt}] + \sum_k w_{jk}\delta_{jk}$. Plugging these budget constraints into the objective function yields

$$u(W_j - C_{j0} - D_{j0} - \sum_k w_{jk} p_{jk}) + \beta E_0 u(C_{j2}\frac{P_{j0}}{P_{j2}} + (1 + i_{jd,0})D_{j0}\frac{P_{j0}}{P_{j,2}} + \sum_k w_{jk}\delta_{jk}) + v(C_{j0}, D_{j0}) \tag{A2}$$

Differentiating this expression with respect to portfolio choices $w_{jk}$,$C_{j0}$, and $D_{j0}$ yields the Euler equations

$$p_{jk} = \frac{\beta E_0 \delta_{jk} u'(c_{j,2})}{u'(c_{j0})} \tag{A3}$$

$$1 = (1 + i_{jd,0})\beta E_0 \frac{u'(c_{j,2})}{u'(c_{j0})}\frac{P_{j0}}{P_{j,2}} + \frac{\frac{\partial v(C_{j0},D_{j0})}{\partial D_{j0}}}{u'(c_{j0})} \tag{A4}$$

$$1 = \beta E_0 \frac{u'(c_{j,2})}{u'(c_{j0})}\frac{P_{j0}}{P_{j,2}} + \frac{\frac{\partial v(C_{j0},D_{j0})}{\partial C_{j0}}}{u'(c_{j0})}. \tag{A5}$$

For a risk-free nominal asset that does not provide liquidity services, its interest rate $i_{j,0}$ satisfies

$$1 = (1 + i_{j,0})\beta E_0 \frac{u'(c_{j,2})}{u'(c_{0t})}\frac{P_{j0}}{P_{j,2}}. \tag{A6}$$

Plugging equation A6 into equation A5 yields

$$1 = \frac{1}{1 + i_{j,0}} + \frac{\frac{\partial v(C_{j0},D_{j0})}{\partial C_{j0}}}{u'(c_{j0})}$$

$$1 - \frac{1}{1 + i_{j,0}} = \frac{\frac{\partial v(C_{j0},D_{j0})}{\partial C_{j0}}}{u'(c_{j0})}.$$

Using these expressions in equation A4 yields

$$1 = \frac{1 + i_{jd,0}}{1 + i_{j,0}} + (1 - \frac{1}{1 + i_{j,0}})\frac{\frac{\partial v(C_{j0},D_{j0})}{\partial D_{j0}}}{\frac{\partial v(C_{j0},D_{j0})}{\partial C_{jt}}}$$

$$i_{j,0} - i_{jd,0} = i_{j,0}\frac{\frac{\partial v(C_{j0},D_{j0})}{\partial D_{j0}}}{\frac{\partial v(C_{j0},D_{j0})}{\partial C_{j0}}}.$$

This is precisely equation 13 from the main text.

Finally, we consider the impact of a change in nominal interest rates when rates are negative. Suppose that, holding real consumption fixed and with $C_{j0} > C^*$, additional cash $C_{j0}$ is injected that increases $G'(C_{j0} - C)$ and therefore pushes the nominal rate $i_{j,0}$ further negative by equation A7. Because consumption does not change and $D_{j0}$ (which pins down $\partial v(C_{j0}, D_{j0})$) is held fixed, we have from equations A4 and A6 that real interest rates are unchanged. As a result, $(1+i_{j,0})\frac{P_{j0}}{P_{j2}}$ and $(1+i_{j,d0})\frac{P_{j0}}{P_{j2}}$ are unchanged and thus the real deposit convenience yield $E_0(\frac{P_{j0}}{P_{j2}})[i_{j,0} - i_{j,d0}]$ is also unchanged by policy.

## A.2 Intermediary's problem

**Statement of Problem** The intermediary maximizes its objective function

$$-[e_{j0}] - E_0[e_{j1} + C(e_{j1})] + \beta E_0 \frac{u'(c_{j2})}{u'(c_{j0})} \delta^I_{j2}. \tag{A7}$$

subject to the budget constraints at times 0,1, and 2

$$e_{j0} + D_{j0} = \sum_k (p_{jk}) q^{I,0}_{jk} \tag{A8}$$

$$e_{j1} = \sum_k (p_{jk,1})[q^{I,1}_{jk} - q^{I,0}_{jk}] \tag{A9}$$

$$\delta^I_2 = \sum_k \delta_{jk} q^{I,1}_{jk,t} - \frac{P_{j0}}{P_{j2}} D_{j0}(1 + i_d) \tag{A10}$$

and the capital constraint

$$\sum_k (1 - (\lambda + \lambda^*_k)) w^{I,1}_{jk} \delta_{jk} \geq (1 + i_{jd,0}) D_{j0} \frac{P_{j0}}{P_{j2}}. \tag{A11}$$

Let $G(e_{j1}) = e_{j1} + C(e_{j1})$ be the total cost of raising intermediary equity at time 1. The intermediary's Lagrangian is, after plugging its budget constraints into its objective function,

$$max_{q^{I,0}_{jk}, q^{I,1}_{jk}, D_{j0}} E_0[D_{j0} - \sum_k (p_{jk}) q^{I,0}_{jk}] - G(\sum_k (p_{jk,1})[q^{I,1}_{jk} - q^{I,0}_{jk}])$$

$$+\beta \frac{u'(c_{j2})}{u'(c_{j0})} [\sum_k \delta_{jk} q^{I,1}_{jk,t} - \frac{P_{j0}}{P_{j2}} D_{j0}(1 + i_d)] + \eta[\sum_k (1 - (\lambda + \lambda^*_k)) \delta_{jk} w^{I,1}_{jk} - \frac{P_{j0}}{P_{j2}} D_{j0}(1 + i_d)]]. \tag{A12}$$

The first-order conditions for portfolio choice are

$$p_{jk} = E_0[\beta \frac{u'(c_2)}{u'(c_0)}[\delta_{jk}] + \eta min_1(\delta_{jk})(1-(\lambda+\lambda_k^*))] \tag{A13}$$

$$p_{jk,1}(1+C'(e_{j1})) = E_1 \beta \frac{u'(c_2)}{u'(c_0)}[\delta_{i,2}] + \eta min_1(\delta_{jk})(1-(\lambda+\lambda_k^*)) \tag{A14}$$

$$p_{jk} = E_0 p_{jk,1}(1+C'(e_{j1})), \tag{A15}$$

where $min_1(\delta_{jk})$ is the payoff of asset k in the state of the world where the intermediary's asset portfolio has the least value at time 2 given what is known at time 1.

To maintain solvency at time 1, the intermediary can lend risk-free to the household at time 1. These risk-free loans are the only asset that can be added to the time 1 intermediary portfolio in addition to those purchased at time 1. These loans have a capital have interest rate $i_{jh}$, which must satisfy the intermediary's portfolio choice first-order conditions as well as the consumption Euler equation of the household who borrows. We have

$$u'(c_{j0}) = (1+i_{jh})\beta E u'(c_{j2}) \tag{A16}$$

$$u'(c_{j0})(1+C'(e_{j1})) = (1+i_{jh})[\beta E u'(c_{j2}) + \eta(1-\lambda)] \tag{A17}$$

$$u'(c_{j0})C'(e_{j1}) = (1+i_{jh})\eta(1-\lambda) \tag{A18}$$

$$\beta E_1 u'(c_{j2}) C'(e_{j1}) = \eta(1-\lambda). \tag{A19}$$

**Convenience Yields at times 0 and 1** We use the intermediary's portfolio choice first-order conditions to charecterize the convenience yield for nominal risk-free assets that it holds. For nominal risk-free assets, the portfolio choice first-order conditions become

$$\frac{1}{1+i_{jk,0}} = E_0 \beta \frac{u'(c_{j2})}{u'(c_{j0})} + \eta(1-(\lambda+\lambda_k^*)) min_1 \frac{P_{j0}}{P_{j2}} \tag{A20}$$

$$\frac{(1+C'(e_{j1}))}{1+i_{jk,1}} = E_1 \beta \frac{u'(c_{j2})}{u'(c_{j0})} + (1-(\lambda+\lambda_k^*)) min_1 \frac{P_{j0}}{P_{j2}} \tag{A21}$$

$$\frac{1}{1+i_{jk,01}} = \frac{1}{1+i_{j,01}} = E_0(1+C'(e_{j1})) \tag{A22}$$

$$\frac{1}{1+i_{jk,0}} = E_0 \frac{(1+C'(e_{j1}))}{1+i_{jk,1}}. \tag{A23}$$

The time 0 deposit issuance first order condition is

$$\frac{1}{1+i_{jd,0}} = E_0 \beta \frac{u'(c_{j2})}{u'(c_{j0})} + \eta min_1 \frac{P_{j0}}{P_{j2}} = \frac{1}{1+i_{j0}} + \eta min_1 \frac{P_{j0}}{P_{j2}}. \tag{A24}$$

This allows us to first relate the convenience yield of deposits to the tightness of constraints the intermediary faces

$$\frac{1}{1+i_{jd,0}} - \frac{1}{1+i_{j0}} = \eta min_1 \frac{P_{j0}}{P_{j2}}. \tag{A25}$$

Equations A20 and A25 imply

$$\frac{1}{1+i_{jk,0}} - \frac{1}{1+i_{j0}} = \eta(1-(\lambda+\lambda_k^*)) min_1 \frac{P_{j0}}{P_{j2}} = (1-(\lambda+\lambda_k^*))[\frac{1}{1+i_{jd,0}} - \frac{1}{1+i_{j0}}]. \tag{A26}$$

Rearranging this expression shows us how the convenience yield for $i_{j0} - i_{jk,0}$ asset k relates to the convenience yield $i_{j0} - i_{jd,0}$ for deposits

$$\frac{i_{j0} - i_{jk,0}}{1+i_{j0}} = (1-(\lambda+\lambda_k^*)))[\frac{1+i_{jk,0}}{1+i_{jd,0}} - \frac{1+i_{jk,0}}{1+i_{j0}}] = \frac{1+i_{jk,0}}{1+i_{jd,0}}(1-(\lambda+\lambda_k^*)))[1 - \frac{1+i_{jd,0}}{1+i_{j0}}]$$

$$i_{j0} - i_{jk,0} = \frac{1+i_{jk,0}}{1+i_{jd,0}}(1-(\lambda+\lambda_k^*)))[i_{j0} - i_{jd,0}]. \tag{A27}$$

This proves the validity of equations 18 and 19 in the main text.

Next, we determine how convenience yields behave at time 1 after the intermediary has faced a shock.

The risk free rate without a convenience yield at time 1 is the price the intermediary would pay for a risk-free asset that does not allow for any additional deposits to be issued. It is priced as

$$\frac{1}{1+i_{j,1}} = E_1 \beta \frac{u'(c_{j2})}{u'(c_{j0})(1+C'(e_{j1}))} \tag{A28}$$

We therefore have

$$\frac{1}{1+i_{jk,1}} - \frac{1}{1+i_{j,1}} = \eta \frac{(1-(\lambda+\lambda_k^*))}{1+C'(e_{j1})} min_1 \frac{P_{j0}}{P_{j2}} \tag{A29}$$

$$= \frac{\beta E_1 u'(c_{j2}) C'(e_{j1})}{1-\lambda} \frac{(1-(\lambda+\lambda_k^*))}{1+C'(e_{j1})} min_1 \frac{P_{j0}}{P_{j2}} \tag{A30}$$

This implies that to a first-order approximation

$$i_{j,1} - i_{jk,1} \approx \frac{C'(e_{j1})}{1+C'(e_{j1})} \beta (E_1 u'(c_{j2})) \frac{(1-(\lambda+\lambda_k^*))}{1-\lambda} min_1 \frac{P_{j0}}{P_{j2}}. \tag{A31}$$

so convenience yields grow when the marginal cost $C'(e_{j1})$ increases. This is consistent with the fact that convenience yields grow during periods of financial distress.

While convenience yields are determined ex post by the severity of intermediary financial constraints, their expected value ex ante is closely related to the leve of nominal interest rates at time 0.

The relationship between convenience yields at time 0 and time 1 follows from equation

A23 which implies

$$\frac{1}{1+i_{jk,0}} - \frac{1}{1+i_{j,0}} = E_0(1+C'(e_{j1}))[\frac{1}{1+i_{jk,1}} - \frac{1}{1+i_{j,1}}] \tag{A32}$$

and thus after a Taylor approximation

$$i_{j,0} - i_{jk,0} \approx E_0(1+C'(e_{j1}))[i_{j,1} - i_{jk,1}] \tag{A33}$$

which proves equation 21 in the main text.

## A.3 International financial arbitrageur

An international financial arbitrageur (such as a hedge fund or dealer bank) is active in derivatives markets around the world. Because of the large demand for global dollar intermediation, it is funded with dollar denominated risk free debt. We assume that its equity is owned by the consumer in country J, which may or may not be the US. It maximizes shareholder value with the objective function

$$-[e_{F0}] - E[e_{F1} + C(e_{F1})] + \beta E \frac{u'(c_{J2})}{u'(c_{J0})}[\delta_2^F] \tag{A34}$$

just like each domestic intermediary. It is subject to a budget constraint akin to that of domestic intermediaries at times 0,1, and 2, except that it can transact in the assets in multiple countries j. Let $e_{jJ,t}$ be the real exchange rate between country j and the home country J of the international arbitrageur at time t and $e_{\$J,t}$ be the real exchange rate with the dollar. The budget constraints can be written as

$$e_{F0} + D_{F0}e_{\$J,0} = \sum_j \sum_k e_{jJ,0}(p_{jk})q_{jk}^{F,0} \tag{A35}$$

$$e_{F1} = \sum_j \sum_k e_{jJ,1}(p_{jk,1})[q_{jk}^{F,1} - q_{jk}^{F,0}] \tag{A36}$$

$$\delta_2^F = \sum_j \sum_k e_{jJ,2}\delta_{jk}q_{jk,t}^{I,1} - e_{\$J,2}\frac{P_{j0}}{P_{j2}}D_{j0}(1 + i_{F,0}). \tag{A37}$$

However, it is unable to issue deposits and instead raises money by transacting with the domestic financial institutions in each country. Liabilities of the international financial institution do not allow domestic financial institutions to back deposits, so it borrow and lends at the "no convenience yield" rate in each currency. It is able to buy arbitrary Arrow-Debreu securities but is financed only by borrowing risk free from the US institution. It faces a constraint that its leverage cannot be greated than some leverage ratio $0 < L_r < 1$. That is, if it has promised $F_2$ in nominal dollar risk free payoffs to lenders at time 2, then we must have $e_{\$J,2}\frac{P_{j0}}{P_{j2}}D_{j0}(1 + i_{F,0}) \leq L_r \sum_j \sum_k e_{jJ,2}\delta_{jk}q_{jk,t}^{F,2}$ in all states of the world. Its Lagrangian can be written as (where $G(x) = x + C(x)$)

$$[D_{F0}e_{\$J,0} - \sum_j \sum_k e_{jJ,0}(p_{jk})q_{jk}^{F,0}] - EG(\sum_j \sum_k e_{jJ,1}(p_{jk,1})[q_{jk}^{F,1} - q_{jk}^{F,0}]) \tag{A38}$$

$$+\beta E\frac{u'(c_{J2})}{u'(c_{J0})}[\sum_j \sum_k e_{jJ,2}\delta_{jk}q_{jk,t}^{I,1} - e_{\$J,2}\frac{P_{j0}}{P_{j2}}D_{j0}(1 + i_{F,0})] \tag{A39}$$

$$+\eta_F[L_r \sum_j \sum_k e_{jJ,2}\delta_{jk}q_{jk,t}^{F,2} - e_{\$J,2}\frac{P_{j0}}{P_{j2}}D_{j0}(1 + i_{F,0})]. \tag{A40}$$

The first order conditions for a dollar risk free asset k and for borrowing dollar debt are at time 0

$$e_{\$J,0} = \beta E\frac{u'(c_{J2})}{u'(c_{J0})}e_{\$J,2}\frac{P_{j0}}{P_{j2}}(1+i_{F,0}) + E\eta_F e_{\$J,2}\frac{P_{J0}}{P_{J2}}(1+i_{F,0}) \tag{A41}$$

$$e_{\$J,0} = \beta E\frac{u'(c_{J2})}{u'(c_{J0})}e_{\$J,2}\frac{P_{j0}}{P_{j2}}(1+i_{\$k,0}) + L_r E\eta_F e_{\$J,2}\frac{P_{J0}}{P_{J2}}(1+i_{\$k,0}) \tag{A42}$$

These first order conditions for dollar risk free assets and borrowing imply

$$\frac{1}{1+i_{\$k,0}} = L_r\frac{1}{(1+i_{F,0})} + (1-L_r)\beta E\frac{u'(c_{J2})}{u'(c_{J0})}\frac{e_{\$J,2}}{e_{\$J,0}}\frac{P_{J0}}{P_{J2}}. \tag{A43}$$

If we define $i_{\$,0}$ to be the dollar risk free rate that solves the equityholder's consumption Euler equation ($\frac{1}{1+i_{\$,0}} = \beta E\frac{u'(c_{J2})}{u'(c_{J0})}\frac{e_{\$J,2}}{e_{\$J,0}}\frac{P_{j0}}{P_{j2}}$) without loosening the leverage constraint at all, then we have

$$\frac{1}{1+i_{\$k,0}} = L_r\frac{1}{(1+i_{F,0})} + (1-L_r)\frac{1}{1+i_{\$,0}} \tag{A44}$$

$$\frac{1}{(1+i_{F,0})} - \frac{1}{1+i_{\$k,0}} = (1-L_r)[\frac{1}{1+i_{\$,0}} - \frac{1}{(1+i_{F,0})}] \tag{A45}$$

$$\frac{i_{\$k,0}-i_{F,0}}{1+i_{\$k,0}} = (1-L_r)\frac{i_{\$,0}-i_F}{1+i_{\$,0}} \tag{A46}$$

$$i_{\$k,0} - i_{F,0} = \frac{1+i_{\$k,0}}{1+i_{\$,0}}(1-L_r)(i_{\$,0}-i_{F,0}) \tag{A47}$$

which proves equation 25 in the main text. The time 1 FOC for dollar borrowing and dollar risk free assets are

$$e_{\$J,0}(1+C'(e_{F1})) = \beta E_1\frac{u'(c_{J2})}{u'(c_{J0})}e_{\$J,2}\frac{P_{j0}}{P_{j2}}(1+i_{F,1}) + \eta_F e_{\$J,2}\frac{P_{J0}}{P_{J2}}(1+i_{F,1}) \tag{A48}$$

$$e_{\$J,0}(1+C'(e_{F1})) = \beta E_1\frac{u'(c_{J2})}{u'(c_{J0})}e_{\$J,2}\frac{P_{j0}}{P_{j2}}(1+i_{\$k,1}) + L_r\eta_F e_{\$J,2}\frac{P_{J0}}{P_{J2}}(1+i_{\$k,1}) \tag{A49}$$

This implies

$$\frac{1}{1+i_{\$k,1}} = L_r \frac{1}{1+i_{F,1}} + (1-L_r)\beta E_1 \frac{u'(c_{J2})}{u'(c_{J0})} \frac{e_{\$J,2}}{e_{\$J,0}(1+C'(e_{F1}))} \frac{P_{j0}}{P_{j2}} \tag{A50}$$

$$(\frac{1}{1+i_{\$k,1}} - \frac{1}{1+i_{F,1}})(1+C'(e_{F1}) = (1-L_r)[\beta E_1 \frac{u'(c_{J2})}{u'(c_{J0})} \frac{e_{\$J,2}}{e_{\$J,0}} \frac{P_{j0}}{P_{j2}} - \frac{1}{1+i_{F,1}}] \tag{A51}$$

Similarly if we define $i_{\$,1}$ to satisfy $\frac{1}{1+i_{\$,1}} = \beta E_1 \frac{u'(c_{J2})}{u'(c_{J0})} \frac{e_{\$J,2}}{e_{\$J,0}(1+C'(e_{F1}))} \frac{P_{j0}}{P_{j2}}$ we have

$$i_{\$k,1} - i_{F,1} = \frac{1+i_{\$k,1}}{1+i_{\$,1}}(1-L_r)(i_{\$,1} - i_{F,1}). \tag{A52}$$

which proves equation 26 in the main text.

# Web Appendix

## B Option counterparty risk and margin requirements

The interest rates that we estimate are only risk-free to the extent that there is no meaningful credit risk in the equity options that we consider. We believe that credit risk is unlikely to impact our estimates for several reasons. First, the option quotes we consider are from exchanges that net trades and require that traders post margin collateral. After this, the option exchange maintains a default fund which is funded by clearing members to absorb losses if margin collateral is insufficient. Finally, an option clearing corporation, which is likely to be supported by a country's central bank in periods of distress, provides the final line of defense.

More formally, all of the quotes that we examine are from exchanges that are backed by a clearing house that meets the international standards and Principles for Financial Market Infrastructures (PFMIs). The PFMIs were introduced in 2012 by the Committee on Payments and Market Infrastructures (CPMI) of the Bank for International Settlements (BIS) and by the Technical Committee of the International Organization of Securities Commissions (IOSCO). In the US and Europe, the Dodd-Frank Act and the European Markets Infrastructure Regulation stipulate that the national regulatory agencies take into consideration the international standards and PFMIs when regulating systematically important central counterparties (CCPs). The goal of the PFMIs is to reduce taxpayer risk and provide protections for cross-border clearing on CCPs even when the financial institutions doing the trading are located in different countries.

The result of adopting the PFMIs is that there are several common layers of protection for systematically important CCPs that mitigate against potential losses from the default of a clearing member.[7] To begin, there are rigorous standards to becoming a clearing member in the first place, so that default occurrences should be rare. The key advantage of a CCP is then its ability to net positions across traders to reduce counterparty risk compared to the bilateral exposures that would occur in an otherwise similar over-the-counter market. In addition, the exchange imposes margin requirements against positions that are adjusted dynamically over time. In the event that a clearing member defaults and their margin collateral is insufficient to cover their losses on the exchange, the clearing house may then call upon the default fund. Default funds are pre-funded by all clearing members with enough capital to withstand the failure of at least two clearing members that create the greatest uncollateralized losses under stress scenarios. Contributions to the default funds are updated on a regular basis, such as monthly, to account for changes in market risks. In the unlikely event that the default fund is exhausted, the clearing house equity capital and that of its parent company are often applied to cover any remaining losses.[8]

Table A1 lists the clearing houses and exchanges for the equity options that we consider in this paper. All of the clearing houses are designated as "Systematically Important Financial Market Utilities" (SIFMUs) by their relevant national regulatory agencies and central banks. The SIFMU designation suggests that their may be implicit support from the regulatory sector in the event that the the exchange default waterfall protections including position netting, margin, the default fund, and the clearing house equity capital contributions are insufficient to cover losses.[9]

[7]Historical examples of clearing member defaults include Drexel Burnham Lambert (1990), Woodhouse, Drake & Carey (1991), Barings (1995), Griffin (1998), Refco (2005), Lehman Brothers (2008), and MF Global (2011).

[8]The clearing houses considered in our paper have strong credit ratings. For example, the OCC is AA-rated, the parent company of Eurex Clearing is Deutsche Börse AG which is AA-rated and has issued a letter of comfort in favor of providing Eurex Clearing with financial funding to comply with its obligations, and the parent company of ICE Clear Europe is Intercontinental Exchange Inc. (ICE) which is A-rated.

[9]For example, during the 1987 stock market crash, the Federal Reserve intervened to ensure that all

Table A1. **Counterparty risk in options markets** Exchanges and clearing houses for trading international index options.

Option Exchanges and Clearing Houses

| Clearing House | Exchange | Currencies | Index | SIFMU | Portfolio Margin |
|---|---|---|---|---|---|
| Options Clearing Corporation | CBOE | USD | S&P 500 | United States Treasury | Methodology |
| Eurex Clearing | Eurex | EUR CHF | EuroStoxx 50 SMI | Bundesbank | Methodology |
| ICE Clear Europe | ICE | GBP | FTSE | Bank of England | Methodology |
| Nasdaq Clearing | Nasdaq OMX Nordic Exchange | SEK DKK | OMXS30 OMXC25 | Riksbank | Methodology |
| Euronext Clearing | Euronext | NOK | OBX 25 | Norges Bank | Methodology |
| Canadian Derivatives Clearing Corporation | Montreal Exchange | CAD | TSX 60 | Bank of Canada | Methodology |
| ASX Clear | ASX | AUD | ASX 200 | Royal Bank of Australia | Methodology |
| Japan Securities Clearing Corporation | Osaka Exchange | JPY | Nikkei 225 | Bank of Japan | Methodology |

Each of the clearing houses also offers portfolio margin which reduces the margin requirements for the box trade. For example, consider implementing the box trade by selling a call and buying a put at a high strike while simultaneously buying a call and selling a put at a low strike. Portfolio margin acknowledges that lending or borrowing at the box rate is transacting in a risk-free cashflow. Without portfolio margin, the trader would have to post margin separately for each leg of the trade, which would make lending or borrowing at the box rate prohibitively expensive. Table A1 provides hyperlinks to the portfolio margin methodology for each exchange and to statements suggesting that options clearing houses are systemtically imporant and likely to receive central bank support in a severe crisis.

derivative contracts were paid off (Bernanke, 1990). Examples of the agencies and central banks that regulate the clearing houses that we consider include the SEC, CFTC, Federal Financial Supervisory Authority (Germany), Swiss National Bank, Swiss Financial Market Supervisory Authority, Bank of England, Bank of Japan, Swedish Financial Supervisory Authority, Norwegian Ministry of Finance, Bank of Canada, and Royal Bank of Australia.

# C Data Appendix

This section describes how we estimated our option-implied rates and lists the sources of our other data. We began with a large database from ICE providing intraday time-stamped option price quotes from the main exchange in each country. Our Swiss Market Index and STOXX options data come from Eurex. Our FTSE 100 option data comes from the ICE exchange. Our NIKKEI data comes from the Osaka Exchange. Our Australian ASX 200 data comes from Australian Securities Exchange. Our Norwegian OBX 25 data comes from the Oslo Stock Exchange. Our Danish OMX Copenhagen 25 and Swedish OMX Stockholm 30 data come from Nasdaq Nordic. On top of this main dataset from ICE, we use the Thompson Reuters Tick database as a backup source of intraday timestamped data. Finally, we use daily OptionMetrics data when neither are available.

For our ICE data, we begin by computing the minute-level median value of each options bid and ask over observations with a positive quote size. We then compute a midpoint of bid and ask. We run our put-call parity regressions in equation 2 minute by minute on our quote midpoints. We perform the same procedure in our Thompson Reuters data over five minute intervals. In both cases, we exclude any regression whose R-squared is below .99999. The median of the remaining regression coefficients is used to compute our daily box rate estimate. For OptionMetrics, we run our put-call parity regression on closing prices to get a daily rate, ignoring days with an R-squared below .99999.

In addition to our box rates, we use IBOR and OIS rates and spot and forward exchange rates from Bloomberg following Du et al. (2018b). Government bond and bill yields come directly from central bank websites. We also use savings deposits rate data (which are average consumer deposit rates, not e.g. rates paid on excess reserves) found across central bank websites. Our corporate bond data comes from the replication data from Liao (2020). Credit default swap spreads come from Markit. Debt to GDP ratio data comes from the

OECD. Central bank policy rates and stock market volatility data are from Haver Analytics. Our data source spreadsheet provides additional specific details.

# Supplementary tables and figures

Table A2. Monthly Exchange Rate Forecast Regressions, following Engel and Wu (2022),separately by country. Monthly regression from Jan 2004 to July 2020.

| Variable | Coefficient | Standard Error | Coefficient | Standard Error |
|---|---|---|---|---|
| $\Delta BoxCIP_{j,t}$ | - 7.38 | 1.92 | - 8.83 | 1.87 |
| $BoxCIP_{j,t-1}$ | - .724 | .849 | - 2.20 | .825 |
| $\Delta CYdiff_{j,t}$ | -3.57 | 2.00 | -3.37 | 1.95 |
| $CYdiff_{j,t-1}$ | -.715 | 1.26 | -1.64 | 1.23 |
| R-squared: | 0.0743 | | 0.1210 | |
| Predicted varible | $\Delta s_{j,t+1}$ | | $\Delta s_{j,t}$ | |
| Country | Euro | | Euro | |

| Variable | Coefficient | Standard Error | Coefficient | Standard Error |
|---|---|---|---|---|
| $\Delta BoxCIP_{j,t}$ | - 3.93 | 1.37 | - 1.65 | 1.37 |
| $BoxCIP_{j,t-1}$ | -.366 | .627 | - .892 | .626 |
| $\Delta CYdiff_{j,t}$ | -3.70 | 1.52 | -3.86 | 1.52 |
| $CYdiff_{j,t-1}$ | -.223 | .969 | 1.67 | .970 |
| R-squared: | 0.0455 | | 0.0402 | |
| Predicted varible | $\Delta s_{j,t+1}$ | | $\Delta s_{j,t}$ | |
| Country | Switzerland | | Switzerland | |

| Variable | Coefficient | Standard Error | Coefficient | Standard Error |
|---|---|---|---|---|
| $\Delta BoxCIP_{j,t}$ | - 6.22 | 2.45 | - 6.70 | 2.38 |
| $BoxCIP_{j,t-1}$ | -2.93 | 1.07 | - 4.08 | 1.04 |
| $\Delta CYdiff_{j,t}$ | -4.82 | 2.44 | -6.12 | 2.37 |
| $CYdiff_{j,t-1}$ | -3.20 | 1.36 | -4.15 | 1.32 |
| R-squared: | 0.0669 | | 0.1119 | |
| Predicted varible | $\Delta s_{j,t+1}$ | | $\Delta s_{j,t}$ | |
| Country | UK | | UK | |

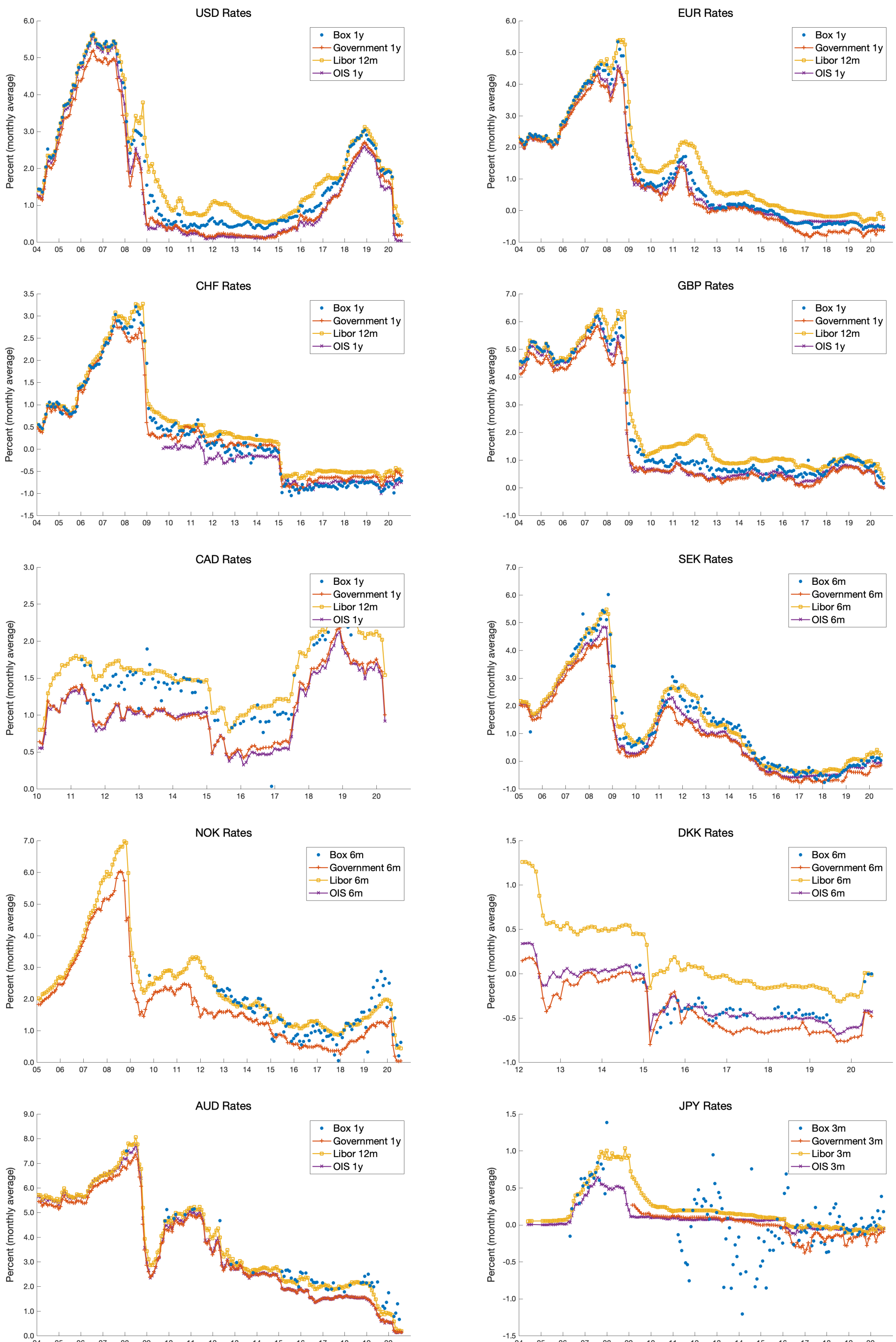


Figure A1. **Time-series of monthly average box rates for USD, EUR, CHF, and GBP** Plots the time-series of monthly average box rates against the monthly average government bond, Libor, and OIS rate. For each currency-month we require at least five days with an estimated box rate to be included in the sample.