

# A Quantity-Driven Theory of Term Premia and Exchange Rates \*

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## Abstract

We develop a model in which specialized bond investors must absorb shocks to the supply and demand for long-term bonds in two currencies. Since long-term bonds and foreign exchange are both exposed to unexpected movements in short-term interest rates, a shift in the supply of long-term bonds in one currency influences the foreign exchange rate between the two currencies, as well as bond term premia in both currencies. Our model matches several important empirical patterns, including the co-movement between exchange rates and term premia, as well as the finding that central banks' quantitative easing policies impact exchange rates. An extension of our model sheds light on the persistent deviations from covered interest rate parity that have emerged since 2008.

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# 1 Introduction

There is a growing recognition that financial intermediaries play an important role in determining foreign exchange (FX) rates (Kouri [1976], Evans and Lyons [2002], Froot and Ramadorai [2005], Gabaix and Maggiori [2015], Itskhoki and Mukhin [2019]). When there are frictions in financial intermediation, exchange rates move in response to shifts in the supply and demand for assets in different currencies, which intermediaries must absorb. Since the wealth of intermediaries in FX markets need not be closely tied to aggregate consumption or conditions in broader financial markets (e.g., equities), this approach can explain the disconnect of exchange rates from macroeconomic fundamentals (Obstfeld and Rogoff [2000]) and the predictability of currency returns (Fama [1984]).

In this paper, we provide a framework for understanding how the detailed structure of financial intermediation impacts foreign exchange rates and show that this approach can shed light on numerous puzzles in the exchange rate literature. We start by assuming that global bond and FX markets are integrated with one another but segmented from other financial markets. We make this assumption for two reasons. First, foreign exchange is conceptually similar to long-term bonds in that both are “interest-rate sensitive” assets: they are heavily exposed to news about future short-term interest rates. Thus, the physical and human capital needed to trade long-term bonds can also be used to trade FX. Indeed, at most major dealer-banks and hedge funds, interest-rate and FX trading are tightly integrated.

Second, concrete empirical motivation for our paper comes from recent work showing that quantitative easing (QE) policies—i.e., large-scale purchases of long-term bonds by central banks—significantly impacted foreign exchange rates and not just long-term bond yields, suggesting important linkages between the two markets. For example, Neely (2011), Bauer and Neely (2014), and Swanson (2017) show that the Fed’s long-term bond purchases were associated with a large depreciation of the U.S. dollar vis-a-vis other major currencies.

A quantity-driven, supply-and-demand approach in the spirit of Tobin (1958, 1969) provides a natural explanation for bond price movements stemming from QE.<sup>1</sup> According to this “portfolio balance” view, holding fixed the expected path of future short-term rates, a reduction in the supply of long-term bonds—such as QE—leads to a fall in long-term bond yields because it reduces the total amount of interest rate risk borne by specialized financial intermediaries. Since the fixed-income market is assumed to be partially segmented from other parts of the broader capital markets, these intermediaries cannot diversify away the interest rate risk they bear and must be paid to absorb shocks to the supply and demand for long-term bonds. This segmentation explains why QE policies—which, while large relative to national bond markets, are small relative to global markets for all financial assets—have a large impact on long-term yields.

Our paper shows that this same quantity-driven, supply-and demand approach can also explain many empirical facts about exchange rates, including their response to QE. The key insight is that, as noted above, foreign exchange and long-term U.S. bonds are exposed to the same primary risk factor—unexpected movements in short-term U.S. interest rates. Thus, if the global

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<sup>1</sup>See, for example, Greenwood and Vayanos (2014), Vayanos and Vila (2019), Hamilton and Wu (2012), D’Amico and King (2013), and Greenwood, Hanson, and Vayanos (2016).

bond and FX markets are integrated with one another, a shift in the supply of long-term U.S. bonds like QE affects the risk premium on both types of assets.

Our baseline model is a straightforward generalization of the Vayanos and Vila (2019) term structure model to a setting with two currencies. Specifically, we consider a model with short-term and long-term bonds in two currencies, which we label the U.S. dollar (USD) and the euro (EUR). Short-term interest rates in each currency are exogenous and evolve stochastically over time. We assume that short rates in the two currencies are positively, but imperfectly, correlated.

The key friction in the model is that the marginal investors in global bond and FX markets—who we call “global bond investors”—are specialized. These investors must absorb exogenous shocks to the supply and demand for long-term bonds in both currencies, as well as demand shocks in the foreign exchange market. Since these specialists have limited risk-bearing capacity, they will only absorb these shocks if the expected returns on long-term bonds in both currencies, as well as foreign exchange, adjust in response.

To solve the model, we must pin down three equilibrium prices: the long-term yield in each currency and the exchange rate between the two currencies—the number of dollars per euro. Equivalently, the equilibrium pins down expected returns on three long-short trades: a “yield curve trade” in each currency—which borrows short-term and lends long-term in that currency—and an “FX trade”—which borrows short-term in dollars and lends short-term in euros.

We first show that this baseline model predicts that shifts in the supply of long-term bonds impact not only term premia, but also the expected returns on the FX trade and hence exchange rates. For instance, an increase in the supply of long-term U.S. bonds raises both the expected excess return on long-term U.S. bonds and the expected return on the borrow-in-dollar lend-in-euro FX trade, leading to a depreciation of the euro versus the dollar.

The key intuition is that the U.S. yield curve trade and the borrow-in-dollar lend-in-euro FX trade have similar exposures to U.S. short rate risk. First, when the U.S. short rate rises unexpectedly, long-term U.S. yields also rise through an expectations hypothesis channel: the expected path of U.S. short rates is now higher, so long-term U.S. yields must rise for long-term U.S. bonds to remain attractive to investors. As a result, the price of long-term U.S. bonds falls, so investors in the U.S. yield curve trade lose money. The borrow-in-dollar lend-in-euro FX trade is also exposed to U.S. short rate risk. When the U.S. short rate rises unexpectedly, the euro depreciates through an uncovered-interest-rate-parity (UIP) channel: since future short rates are now expected to be higher in the U.S. than in Europe, the euro must fall and then be expected to appreciate for short-term euro bonds to remain attractive. Thus, the FX trade suffers losses at the same time as the U.S. yield curve trade.

Now consider the effect of an increase in the supply of long-term U.S. bonds—e.g., because the Federal Reserve announces it is going to unwind its QE policies. Following this outward supply shift, global bond investors will be more exposed to future shocks to short-term U.S. interest rates. As a result, the price of bearing U.S. short rate risk must rise. Since long-term U.S. bonds are exposed to U.S. short rate risk, this leads to a rise in the term premium component of long-term U.S. yields. It also leads to a rise in the risk premium on the borrow-in-dollar lend-in-euro FX trade, which is similarly exposed to U.S. short rate risk. As a result, the euro must depreciate

against the dollar and will be expected to appreciate going forward.<sup>2</sup>

The baseline model makes several additional predictions. First, we show that bond supply shocks should have a larger impact on the bilateral exchange rate when the correlation between the two countries' short rates is lower. For example, the USD-JPY exchange rate should be more responsive to U.S. QE than the USD-EUR exchange rate because Japanese short rates are less correlated with U.S. short rates than are Euro short rates. Second, our model matches the otherwise puzzling finding in Lustig, Stathopoulos, and Verdelhan (2019) that the return to the FX trade declines if one borrows long-term in one currency to lend long-term in the other. In our model, this pattern arises because the "long-term" FX trade has offsetting exposures to short-rate shocks, making it less risky for global bond investors than the standard FX trade involving short-term bonds.

After fleshing out these basic predictions, we show that our approach delivers a unified account linking two well-known facts about the predictability of bond and foreign exchange returns. First, Campbell and Shiller (1991) showed that the yield curve trade earns positive expected returns when the yield curve is steep. Second, Fama (1984) showed that the FX trade earns positive expected returns when the euro short rate exceeds the U.S. one. With one additional assumption, our model can simultaneously match these two facts. Specifically, we assume that global bond investors' exposure to the FX trade is increasing in the foreign exchange rate due to balance-of-trade driven flows. The idea is that when the euro is strong, U.S. net exports to Europe rise. This in turn creates higher demand from U.S. exporters to swap the euros they receive from their European sales into dollars, which global bond investors must accommodate. This assumption, which is needed in Gabaix and Maggiori (2015) to match the Fama (1984) result, immediately delivers the Campbell-Shiller (1991) result in our model for the yield curve trades in both currencies.<sup>3</sup>

To see the intuition, suppose that the euro short rate is higher than the U.S. short rate. By standard UIP logic, the euro will be strong relative to the dollar. Our assumed trade flows mean that global bond investors must bear greater euro exposure when the euro is strong. This raises the expected returns on the borrow-in-dollar lend-in-euro FX trade. As a result, the expected return on the FX trade is increasing in the difference between euro and U.S. short rates as in Fama (1984). This is the logic of Gabaix and Maggiori (2015). In our model, because global bond investors will lose money on their FX positions if U.S. short rates rise, the equilibrium expected returns on the U.S. yield curve trade must simultaneously rise. At the same time, the yield curve will be steeper in the U.S. than the euro area because U.S. short rates are lower and expected to mean-revert. Thus, the model will also match Campbell and Shiller's (1991) finding that a steep yield curve predicts high excess returns on long-term bonds.

We then extend our model in several ways to explore how the detailed structure of finan-

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<sup>2</sup>We have discussed these effects in terms of U.S. short rate risk, but they apply symmetrically to euro short rate risk. The supply of long-term euro bonds has the opposite effect on the USD-EUR exchange rate as the supply of long-term U.S. bonds.

<sup>3</sup>Symmetrically, the assumption used by Vayanos and Vila (2019) to match the Campbell-Shiller (1991) fact—that the net supply of long-term bonds is decreasing in long-term yields—immediately delivers the Fama (1984) pattern for foreign exchange in our model.

cial intermediation impacts foreign exchange rates. We first explore the post-2008 violations of covered-interest-rate parity (CIP) recently documented by Du, Tepper, and Verdelhan (2018). When CIP holds, the short-term U.S. “cash” rate equals the “synthetic” U.S. short rate, which is obtained by investing in short-term euro bonds and using FX forward contracts to hedge the associated FX risk. Since CIP violations imply the existence of riskless profits, they cannot be explained simply by invoking segmentation and limited risk-bearing capacity. Therefore, we make three changes to the model. First, we split our global bond investors, so half are domiciled in the U.S. and half are domiciled in the eurozone. Second, we assume the only intermediaries who can engage in riskless CIP arbitrage trades—i.e., borrowing at the synthetic U.S. rate to lend at the cash U.S. rate—are a set of banks that face non-risk-based balance sheet constraints. Third, we assume that bond investors must use FX forwards if they want to make FX-hedged investments in long-term bonds outside their home domiciles. Under these assumptions, we show that deviations from CIP co-move with spot exchange rates as documented by Du, Tepper, and Verdelhan (2018) and Jiang, Krishnamurthy, and Lustig (2019). The intuition is that a positive U.S. bond supply shock generates demand from Euro investors to buy U.S. long-term bonds and hedge the associated FX risk using FX forwards. Banks accommodate this hedging demand and lay off the accompanying FX risk by engaging in riskless CIP arbitrage trades. Since these riskless CIP arbitrage trades use scarce balance-sheet capacity, banks will only accommodate investor hedging demand if there are deviations from CIP, leading to comovement between CIP deviations and spot FX rates.

We next explore what happens if intermediation is further segmented within global bond and FX markets. Specifically, we replace some of our flexible global bond investors with local-currency bond specialists, who can only trade short- and long-term bonds in their local currency, as well as with specialists who only conduct the FX trade. Introducing this further specialization delivers two additional effects relative to the baseline model. First, shocks to the supply of long-term bonds in either currency generally have a larger impact on the exchange rate than in the baseline model. This effect arises because further segmentation effectively reduces bond investors’ collective risk-bearing capacity. Second, shocks to the supply of long-term bonds trigger FX trading flows between different investor types. In this way, we endogenize the FX flows in Gabaix and Maggiori (2015), ascribing them to capital markets forces.

In a third extension, we introduce interest-rate insensitive assets—e.g., equities—that are not exposed to movements in interest rates. In our baseline model, shocks to the supply-and-demand for rate-insensitive assets have no effect on exchange rates because they do not change the amount of interest rate risk borne by global bond investors. However, in the presence of deviations from CIP or other FX hedging frictions, these shocks can impact exchange rates because they generate demands for different currencies, which global bond investors must accommodate. In other words, the CIP deviations that have emerged since 2008 significantly increase the set of capital market flows that can impact exchange rates.

Our paper is most closely related to work studying portfolio balance effects in currency markets (e.g., Kouri [1976], Evans and Lyons [2002], Froot and Ramadorai [2005], Gabaix and Maggiori [2015]). In these models, the disconnect between exchange rates and macroeconomic fundamen-

tals is explained by a disconnect between intermediaries in currency markets and the broader economy.<sup>4</sup> Our paper is also closely related to papers studying portfolio balance effects in bond markets.<sup>5</sup> Our key contribution is to show that the structure of financial intermediation, which links shocks hitting the intermediaries in FX markets to shocks in the bond market, helps to explain several important empirical patterns.

The closest paper to ours is independent work by Gourinchas, Ray, and Vayanos (GRV 2020). GRV also study a two-currency generalization of the Vayanos and Vila (2019) term structure model. While we work in discrete time with only a short- and long-term bond in each currency, GRV work in continuous time and consider a continuum of zero-coupon bonds in each currency. Despite these technical differences, our baseline theoretical results in Section 3 below have close analogs in their setting and vice versa. Nevertheless, there are a number of important differences between the two papers, and we believe they are complementary. For instance, GRV numerically calibrate their model to data on the U.S. and U.K. yield curves and then use the calibrated model to conduct numerical policy experiments. In contrast, we explore theoretically CIP violations, other FX hedging frictions, and the role of additional segmentation within the global bond market. We also establish a number of empirical results that support the key predictions from our baseline model. In summary, while the results in Section 3 below are similar in spirit to those in GRV, the results in Sections 2, 4 and 5 are almost entirely distinct.

Our paper is also related to the vast literature taking a consumption-based, representative agent approach to exchange rates.<sup>6</sup> In contrast to our quantity-driven, segmented-markets model, these traditional asset pricing theories struggle to explain why supply shocks—e.g., central bank QE policies—impact foreign exchange rates and other asset prices. As Woodford (2012) explains, this is because a mere “reshuffling” of assets between households and the central bank does not change the pricing kernel in standard theories. Furthermore, as we detail below, consumption-based models generally imply very different relationships between exchange rates and interest rates than our model. For instance, in consumption-based models, the expected return on the borrow-in-dollar lend-in-euro FX trade is negatively correlated with the difference between U.S. and euro term premia. By contrast, in our model, the correlation is positive.

The remainder of the paper is organized as follows. In Section 2, we present some empirical evidence that motivates our theoretical analysis. Section 3 presents the baseline model. Section 4 extends the model to shed light on deviations from CIP. Section 5 presents an extension that allows for further segmentation within the global bond and FX markets and considers the implications when investors are constrained in their ability to hedge FX risk. Section 6 concludes.

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<sup>4</sup>A literature in international economics, including Farhi and Werning (2012) and Itshoki and Mukhin (2019), features reduced-form “UIP shocks,” which similarly disconnect exchange rates from macro fundamentals.

<sup>5</sup>See, for example, Vayanos and Vila (2019), Greenwood, Hanson, and Stein (2010), Greenwood and Vayanos (2014), Hanson (2014), Hanson and Stein (2015), Malkhozov, Mueller, Vedolin, and Venter (2016), Hanson, Lucca, and Wright (2018), and Haddad and Sraer (2019).

<sup>6</sup>Contributions to this literature include Backus, Kehoe, and Kydland (1992), Backus and Smith (1993), Backus, Foresi, and Telmer (2001), Verdelhan (2010), Colacito and Croce (2011, 2013), Bansal and Shaliastovich (2012), Lustig, Roussanov, and Verdelhan (2014), Farhi and Gabaix (2016), and many others.

## 2 Motivating evidence

To motivate our theoretical analysis, we present evidence for three related propositions. First, exchange rates appear to be about as sensitive to changes in long-term interest rate differentials as to changes in short-term interest rate differentials. Second, the component of long-term rate differentials that matters for exchange rates appears to be a forecastable term premium differential, rather than the future path of short rates. And third, differences in term premia that move exchange rates appear to be partially quantity-driven, as they are responsive to QE announcements. This last feature cannot be captured by complete-markets, representative-agent models of exchange rates, since in such models supply shocks like QE are mere reshufflings of assets between households and the central bank and have no effect on asset prices.

### 2.1 Contemporaneous movements in foreign exchange rates

Table 1 shows monthly panel regressions of the form

$$\Delta_h q_{c,t} = A_c + B \times \Delta_h (i_{c,t}^* - i_t) + D \times \Delta_h (y_{c,t}^* - y_t) + \Delta_h \varepsilon_{c,t}, \quad (1)$$

where  $\Delta_h q_{c,t}$  is the quarterly ( $h = 3$ ) or annual ( $h = 12$ ) log change in currency  $c$  vis-a-vis the U.S. dollar (USD),  $i_{c,t}^*$  and  $i_t$  denote the foreign and U.S. short-term interest rates, and  $y_{c,t}^*$  and  $y_t$  are the foreign and U.S. long-term interest rates. Positive values of  $\Delta_h q_{c,t}$  denote appreciation of the foreign currency versus the dollar. The sample includes monthly observations between 2001 and 2017 for the euro (EUR), British pound (GBP), and Japanese yen (JPY). In Table 1, we measure the short-term interest rate as the 1-year government bond yield and the long-term interest rate as the 10-year zero-coupon government bond yield.<sup>7</sup> The regressions include currency fixed effects and exploit within currency time-series variation. They are estimated using monthly data and contain overlapping observations, so we report Driscoll-Kraay (1998) standard errors—the panel analog of Newey-West (1987).

Column (1) shows the well-known result, consistent with standard UIP logic, that the foreign currency appreciates in response to an increase in the foreign-minus-dollar short rate differential. A one percentage point increase in the short rate differential in a given quarter leads to a 4.68 percentage point appreciation of the foreign currency.

Column (2) shows a new result: currencies appear to be at least as responsive to changes in long-term interest rates as they are to changes in short-term interest rates. Specifically, the long-term yield differential,  $\Delta_h (y_{c,t}^* - y_t)$ , enters with a coefficient of 4.37, comparable to the coefficient of 3.51 on short rate differential,  $\Delta_h (i_{c,t}^* - i_t)$ . Columns (3) and (4) present specifications that break the rate differentials into their foreign and U.S. dollar components:

$$\Delta_h q_{c,t} = A_c + B_1 \times \Delta_h i_{c,t}^* + B_2 \times \Delta_h i_t + D_1 \times \Delta_h y_{c,t}^* + D_2 \times \Delta_h y_{c,t} + \Delta_h \varepsilon_{c,t}. \quad (2)$$

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<sup>7</sup>We obtain data on exchange rates from Bloomberg. Data on U.S. Treasury zero-coupon bond yields is from Gürkaynak, Sack, and Wright (2007). For the euro, we use data on German government zero-coupon bond yields from the Bundesbank. Data on the U.K. and Japanese government zero-coupon yield curves are from the Bank of England and the Bank of Japan, respectively.

Foreign and U.S. short-term rates enter with opposite signs in column (3).<sup>8</sup> Similarly, the foreign and U.S. long-term yields enter with coefficients of 5.09 and  $-4.83$  in column (4), consistent with the idea that changes in the term premium differential impact the exchange rate.

Columns (5) to (8) repeat the analysis from columns (1) to (4), but change the forecasting horizon to be annual. Compared to the prior specifications using quarterly changes, the coefficient on the foreign-minus-U.S. short rate differential is smaller in magnitude (0.80 in column (6) versus 3.51 in column (2)), but the coefficient on the long rate differential is larger (7.37 in column (6) versus 4.37 in column (2)).

The evidence in Table 1 suggests that exchange rates react to movements in bond term premia. However, the change in the 10-year bond yield is not a clean measure of changes in term premia: it contains both changes in term premia and changes in expected future short-term interest rates. A potentially cleaner, albeit still imperfect, measure of movements in term premia is the change in forward interest rates at distant horizons. Distant forward rates reflect expectations of short-term interest rates in the distant future plus a term premium component. The idea is that there is typically relatively little news about short-term rates in the distant future, so changes in distant forward rates primarily reflect term movements in premia (Hanson and Stein [2015]). Indeed, there is a large literature showing that forward rates forecast the excess returns on long-term bonds (Fama and Bliss [1987], Cochrane and Piazzesi [2005]).

Table 2 presents regressions of the same form as in Table 1, but now using distant forward rates ( $f_{c,t}^*$  and  $f_t$ ) instead of long-term yields ( $y_{c,t}^*$  and  $y_t$ ) as our proxy for term premia. The distant forward we use is the 3-year 7-year forward government bond yield. Compared with Table 1, the coefficients on the short-rate differentials are slightly larger in magnitude and the coefficients on the long-rate differentials are slightly smaller in magnitude, but the latter remain highly economically and statistically significant. For example, in column (2) of Table 2, the short- and long-rate differentials enter with coefficients of 4.72 and 2.99, as compared to coefficients of 3.51 and 4.37 in column (2) of Table 1. Thus, Table 2 reinforces the conclusion that changes in the term premium component of long-term bond yields are associated with movements in foreign exchange rates.

### 2.1.1 Robustness

We have explored several variations on our baseline specifications. We find similar results with different proxies for short-term rates, including the 2-year yield, and different proxies for distant forward rates, including the 1-year 9-year forward. We also find similar results if we expand the panel to also include the Australian dollar, Canadian dollar, and Swiss franc.

However, it is important to note that our results are sample dependent. They are statistically and economically strong when we start our analysis in 2001 or later but become significantly weaker if we extend the sample back further into the 1990s and 1980s. One possible explanation

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<sup>8</sup>Changes in foreign short rates attract a larger coefficient than changes in domestic short rates. This is what one would expect if innovations to foreign rates are more persistent than their domestic counterparts. Alternately, this result would also arise if the U.S. set world short rates and foreign short rates move less than one-for-one with U.S. short rates—i.e., if  $i_{c,t}^* = \beta_c^* i_t + \xi_{c,t}^*$  where  $\beta_c^* \in (0, 1)$ .



for this sample dependence is that inflation was more volatile in earlier periods. Our theory speaks to real interest rates and exchange rates, which may be swamped by fluctuations in nominal price inflation in earlier data. A second possibility is that currency and long-term bond markets were less integrated in earlier periods. The development of a more integrated global bond and currency market may have taken place in the 1990s, especially after the introduction of the euro in 1999 (Mylonidis and Kollias [2010], Pozzi and Wolswijk [2012]). As we discuss in Section 5.1, one would not expect a tight linkage between exchange rates and bond term premia if bond markets are highly segmented from the foreign exchange market.

## 2.2 Forecasting bond and foreign exchange returns

In Tables 1 and 2, we used changes in long-term yields and forward rates as proxies for movements in the term premium on long-term bonds. If this interpretation is correct, these same measures should also forecast excess returns on long-term bonds over short-term bonds in their respective currencies. Table 3 tests this prediction by running regressions of the form

$$rx_{c,t \rightarrow t+h}^{y*} - rx_{t \rightarrow t+h}^y = A_c + B \times (i_{c,t}^* - i_t) + D \times (f_{c,t}^* - f_t) + \varepsilon_{c,t \rightarrow t+h}, \quad (3)$$

and

$$rx_{c,t \rightarrow t+h}^{y*} - rx_{t \rightarrow t+h}^y = A_c + B_1 \times i_{c,t}^* + B_2 \times i_t + D_1 \times f_{c,t}^* + D_2 \times f_t + \varepsilon_{c,t \rightarrow t+h}. \quad (4)$$

Here  $rx_{c,t \rightarrow t+h}^{y*}$  denotes  $h$ -month returns on long-term bonds in country  $c$  in excess of the short-term interest rate in that country.  $rx_{t \rightarrow t+h}^y$  denotes  $h$ -month excess returns on long-term bonds in the U.S. As in Tables 1 and 2, the sample period runs from 2001 to 2017 and consists of the USD-EUR, USD-GBP, and USD-JPY currency pairs.

The table shows that distant forward rates predict future excess bond returns at 3- and 12-month horizons. For example, column (2) shows that if the foreign distant forward rate is one percentage point higher than the U.S. distant forward rate, then, over the next three months, excess returns (in foreign currency) on long-term foreign bonds exceed excess returns (in dollars) on long-term U.S. bonds by 1.68 percentage points on average. Similar results obtain at an annual forecasting horizon.

In Table 4, we forecast excess returns on investments in foreign currency. The specifications parallel those in Table 3, but the dependent variable is now the log excess return on an investment in foreign currency that borrows for  $h$ -months at the U.S. short-term rate  $i_t$  and invests at the foreign short-term rate  $i_{c,t}^*$ . In other words, the regressions take the form:

$$rx_{c,t \rightarrow t+h}^q = A_c + B \times (i_{c,t}^* - i_t) + D \times (f_{c,t}^* - f_t) + \varepsilon_{c,t \rightarrow t+h}, \quad (5)$$

and

$$rx_{c,t \rightarrow t+h}^q = A_c + B_1 \times i_{c,t}^* + B_2 \times i_t + D_1 \times f_{c,t}^* + D_2 \times f_t + \varepsilon_{c,t \rightarrow t+h}, \quad (6)$$

where  $rx_{c,t \rightarrow t+h}^q \equiv q_{c,t+h} - q_{c,t} + (h/12) \times (i_{c,t}^* - i_t)$  is the  $h$ -month excess return (in dollars) on foreign currency  $c$ .

The results in Table 4 are consistent with a risk premium interpretation of our earlier results. For example, in column (2), an increase in the foreign-minus-U.S. distant forward rate differential negatively predicts 3-month currency returns with a coefficient of  $-1.47$  ( $p$ -value  $< 0.01$ ).<sup>9</sup> This means that if the foreign distant forward rate rises by one percentage point relative to the U.S. distant forward rate, investors can expect a 1.47 percentage point lower return on the trade that borrows in dollars and lends in foreign currency over the next 3 months. This is consistent with our results in Tables 1 and 2. For instance, Table 2 shows that increases in the foreign-minus-U.S. distant forward differential are associated with a contemporaneous appreciation of the foreign currency. Table 4 shows that this increase in distant forward rate differentials is associated with a subsequent depreciation of foreign currency and thus low foreign currency returns.<sup>10</sup>

### 2.3 Central bank quantitative easing announcements

Our results so far are consistent with the idea that bond term premia play a role in driving the foreign exchange risk premium. That said, our prior results do not tell us precisely what drives bond term premia in the first place and, thus, do not necessarily single out a supply-and-demand approach to risk premium determination. As a final piece of more direct motivating evidence for our quantity-driven approach, we turn our attention to central bank announcements about changes in the net supply of long-term bonds. As noted earlier, many studies have documented the impact of central bank quantitative easing (QE) announcements on long-term bond yields (Gagnon et al [2011], Krishnamurthy and Vissing-Jorgensen [2011], and Greenwood, Hanson, and Vayanos [2016]). Drawing on these previous studies, we isolate periods where we have more confidence that changes in long-term yields and distant forward rates reflect quantity-driven news about term premia, and show that these changes in term premia typically occur alongside changes in exchange rates.

Figure 1 illustrates our approach. Expanding the list in Mamaysky (2018), we construct a list of large-scale asset purchase announcements by the U.S. Federal Reserve, the European Central Bank, the Bank of England, and the Bank of Japan. For a QE announcement on date  $t$ , we show the appreciation of the foreign exchange rate and the movement in foreign-minus-U.S. distant forward rates from day  $t - 2$  to day  $t + 2$ . For the U.S. announcements, we show the average appreciation of the dollar relative to euro, pound, and yen versus the movement in U.S. long-term forward rates minus the average movement in forward rates for the euro, pound, and yen. For the other three currencies, we show their appreciation relative to the dollar versus the movement in the local currency forward rate minus the dollar forward rate.

Consider the Fed’s announcement on March 18, 2009 that it would expand its purchases of long-term U.S. bonds to \$1.75 trillion from a previously announced \$600 billion. As can be seen in Figure 1, distant U.S. forward rates fell by more than 40 basis points relative to those in other countries in the days surrounding this announcement, and the dollar depreciated by approxi-

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<sup>9</sup>The coefficient on the short-term interest rate differential is essentially zero, consistent with evidence that the “FX carry trade” that borrows in low short-rate countries and invests in high short-rate countries has been weak in recent decades (e.g., Jylha and Suominen [2011]).

<sup>10</sup>Boudoukh, Richardson, and Whitelaw (2016) obtain a similar result.

mately 4 percent vis-a-vis the euro, pound, and yen basket. For many announcements, neither distant forwards nor currencies move by much, perhaps because the announcements were anticipated or because they fell short of the market’s expectations of future bond purchases. However, Figure 1 shows that announcements that were associated with significant relative movements in distant forward rates were typically associated with sizable currency depreciations.

In Table 5, we focus our attention to these QE announcements and estimate the regressions akin to those in Table 2, namely:

$$\Delta_4 q_{c,t+2} = A + B \times (\Delta_4 i_{c,t+2}^* - \Delta_4 i_{t+2}) + D \times (\Delta_4 f_{c,t+2}^* - \Delta_4 f_{t+2}) + \Delta_4 \varepsilon_{c,t+2}, \quad (7)$$

and

$$\Delta_4 q_{c,t+2} = A + B_1 \times \Delta_4 i_{c,t+2}^* + B_2 \times \Delta_4 i_{t+2} + D_1 \times \Delta_4 f_{c,t+2}^* + D_2 \times \Delta_4 f_{t+2} + \Delta_4 \varepsilon_{c,t+2}. \quad (8)$$

Whereas in Tables 1 and 2 we studied quarterly and annual changes, here we restrict attention to the 55 QE-related announcements in the U.S., Eurozone, U.K., and Japan. The regressions have more than 55 observations because for the 20 U.S. QE announcements, we include data points for each of the euro, pound, and yen responses; this is similar to looking at the average change in the dollar relative to these three currencies. To avoid double-counting events from a statistical perspective, we cluster our standard errors by announcement date. As in Figure 1,  $\Delta_4 q_{c,t+2}$  is the four-day change in the exchange rate, from two-days before the announcement to the close two-days after; all other variables are measured over the same period.

Column (2) shows the main result. Both changes in short-term interest rate differentials and changes in long-term forward rate differentials measured around QE-news dates are positively related to movements in exchanges rates. Column (4) shows that the effects of foreign and U.S. term premia on exchange rate movements are approximately symmetric and of opposite sign, attracting coefficients of 3.2 and  $-2.5$  respectively.

In sum, the evidence suggests that, not only is there a close connection between bond term premia and FX risk premia, but that both of these premia are partially driven by shocks to bond supply. These stylized facts are the motivation for the model that we turn to next.

### 3 Baseline model

Our baseline model generalizes the Vayanos and Vila (2019) term-structure model to a setting with two currencies, say, the U.S. dollar and the euro. We consider a model with short- and long-term bonds in domestic currency (dollars) and foreign currency (euros). There is an exogenously given short-term interest rate in each currency. The key friction is that the global bond market is partially segmented from the broader capital market: we assume the marginal investors in the global bond market—who we call “global bond investors”—are specialized investors. These bond investors must absorb exogenous shocks to the supply and demand for long-term bonds in both currencies, as well as shocks in the foreign exchange market. Since they are concerned about the risk of near-term losses on their imperfectly diversified portfolios, specialists will only absorb

these shocks if expected returns on bonds and FX adjust.

### 3.1 Model setup

The model is set in discrete time. To maintain tractability, we assume that asset prices (or yields) and expected returns are linear functions of a vector of state variables. To model fixed income assets, we (i) substitute log returns for simple returns throughout and (ii) use Campbell-Shiller (1988) linearizations of log returns. We view (i) and (ii) as linearity-generating modelling devices that do not qualitatively impact our conclusions.

#### 3.1.1 Financial assets

There are four assets in the model: short- and long-term bonds in both domestic (dollars) and foreign (euros) currency. We then describe the foreign exchange market.

**Short-term domestic bonds** The log short-term interest rate in domestic currency between time  $t$  and  $t + 1$ , denoted  $i_t$ , is known at time  $t$  and follows an exogenous stochastic process described below. Thus, we assume short-term domestic bonds are available in perfectly elastic supply—i.e., investors can borrow or lend any desired quantity in domestic currency from  $t$  to  $t + 1$  at  $i_t$ .<sup>11</sup> All interest rates and exchanges rates in the model are real.

**Long-term domestic bonds** The long-term domestic bond is a default-free perpetuity. At time  $t$ , long-term domestic bonds are available in a given net supply  $s_t^y$  which follows an exogenous stochastic process described below. As shown in the Online Appendix, the log return in domestic currency on long-term domestic bonds from  $t$  to  $t + 1$  is approximately:

$$r_{t+1}^y = \frac{1}{1-\delta}y_t - \frac{\delta}{1-\delta}y_{t+1} = y_t - \frac{\delta}{1-\delta}(y_{t+1} - y_t), \quad (9)$$

where  $y_t$  is the log yield-to-maturity on domestic bonds,  $\delta \in (0, 1)$ , and  $D = 1/(1 - \delta)$  is the duration of the long-term bond—i.e., the sensitivity of the bond’s price to its yield.<sup>12</sup> A larger  $\delta$  corresponds to an economy with longer-term bonds, and the return on long-term bonds is the sum of a “carry” component,  $y_t$ , that investors earn if yields do not change and a capital gain component,  $-(\delta/(1 - \delta))(y_{t+1} - y_t)$ , due to changes in yields.

Iterating Eq. (9) forward and taking expectations, the domestic long-term yield can be decomposed into an expectations hypothesis component and a term premium component:

$$y_t = (1 - \delta) \sum_{j=0}^{\infty} \delta^j E_t[i_{t+j} + r x_{t+j+1}^y], \quad (10)$$

<sup>11</sup>We think of monetary policy as determining short-term rates outside of the model. The domestic and foreign central banks independently pursue monetary policy in their currencies by posting an interest rate and then elastically borrowing and lending at that rate.

<sup>12</sup>This approximation for default-free coupon-bearing bonds appears in Campbell (2018) and is an approximate generalization of the fact that the log-return on  $n$ -period zero-coupon bonds from  $t$  to  $t + 1$  is *exactly*  $r_{t+1}^n = n y_t^n - (n - 1) y_{t+1}^{n-1}$  where, for instance,  $y_t^n$  is the log yield on  $n$ -period zero-coupon bonds at  $t$ .

where  $rx_{t+1}^y \equiv r_{t+1}^y - i_t$  is the excess return on domestic long-term bonds over the domestic short rate. In other words,  $rx_{t+1}^y$  is the log excess return on the “yield curve trade” in domestic currency—i.e., the trade that borrows short-term and lends long-term in domestic currency.

**Short-term foreign bonds** Short-term foreign bonds mirror short-term domestic bonds. The log short-term riskless rate in foreign currency between time  $t$  and  $t + 1$  is denoted  $i_t^*$ .

**Long-term foreign bonds** Long-term foreign bonds mirror long-term domestic bonds. They are available in an exogenous, time-varying net supply  $s_t^{y*}$ . The log return in foreign currency on long-term foreign bonds is given by the analog of Eq. (9), and the log yield-to-maturity on foreign bonds,  $y_t^*$ , is given by the analog of Eq. (10).  $rx_{t+1}^{y*} \equiv r_{t+1}^{y*} - i_t^*$  denotes the excess return on the “yield curve trade” in foreign currency.

**Foreign exchange** Let  $Q_t$  be the foreign exchange rate defined as units of domestic currency per unit of foreign currency. An exchange rate of  $Q_t$  means that an investor can exchange foreign short-term bonds with a market value of one unit of foreign currency for domestic short-term bonds with a market value of  $Q_t$  in domestic currency. Thus, a rise in  $Q_t$  means an appreciation of the foreign currency relative to domestic currency. Let  $q_t$  denote the log exchange rate.

Consider the excess return on foreign currency from time  $t$  to  $t + 1$ —i.e., the FX trade that borrows short-term in domestic currency and lends short-term in foreign currency. The log excess return on foreign currency is approximately:

$$rx_{t+1}^q = (q_{t+1} - q_t) + (i_t^* - i_t). \quad (11)$$

Thus, the excess return on foreign currency is the sum of the interest rate differential,  $i_t^* - i_t$ , and the change in exchange rates,  $(q_{t+1} - q_t)$ . Assuming the exchange rate is stationary with a steady-state level of 0—i.e., that purchasing power parity holds in the long run, we can iterate forward and take expectations to obtain:

$$q_t = \sum_{j=0}^{\infty} E_t[(i_{t+j}^* - i_{t+j}) - rx_{t+j+1}^q], \quad (12)$$

as in Froot and Ramadorai (2005). Thus, the exchange rate is the sum of a UIP component and an FX risk premium component.

### 3.1.2 Risk factors

Investors face two types of risk in our model: interest rate risk and supply risk. First, long-term bonds and foreign exchange positions are exposed to interest rate risk. For example, both long-term domestic bonds and foreign currency will suffer unexpected losses if short-term domestic rates rise unexpectedly. Second, both long-term bonds and FX positions are exposed to supply risk: stochastic supply shocks impact equilibrium bond yields and exchange rates, holding fixed the expected future path of short rates.

**Short-term interest rates** We assume short-term interest rates in domestic and foreign currencies follow symmetric AR(1) processes with correlated shocks:

$$i_{t+1} = \bar{i} + \phi_i(i_t - \bar{i}) + \varepsilon_{i_{t+1}}, \quad (13a)$$

$$i_{t+1}^* = \bar{i} + \phi_i(i_t^* - \bar{i}) + \varepsilon_{i_{t+1}^*}, \quad (13b)$$

where  $\bar{i} > 0$ ,  $\phi_i \in (0, 1)$ ,  $Var_t[\varepsilon_{i_{t+1}}] = Var_t[\varepsilon_{i_{t+1}^*}] = \sigma_i^2 > 0$ , and  $\rho = Corr[\varepsilon_{i_{t+1}}, \varepsilon_{i_{t+1}^*}] \in [0, 1]$ .

**Net bond supplies** We assume the net supplies of long-term domestic bonds ( $s_t^y$ ) and long-term foreign bonds ( $s_t^{y*}$ ) follow symmetric AR(1) processes. These net bond supplies are the market value of long-term domestic and foreign bonds, both denominated in units of domestic currency, that arbitrageurs must hold in equilibrium. Specifically, we assume:

$$s_{t+1}^y = \bar{s}^y + \phi_{sy}(s_t^y - \bar{s}^y) + \varepsilon_{s_{t+1}^y}, \quad (14a)$$

$$s_{t+1}^{y*} = \bar{s}^y + \phi_{sy}(s_t^{y*} - \bar{s}^y) + \varepsilon_{s_{t+1}^{y*}}, \quad (14b)$$

where  $\bar{s}^y > 0$ ,  $\phi_{sy} \in [0, 1)$ , and  $Var_t[\varepsilon_{s_{t+1}^y}] = Var_t[\varepsilon_{s_{t+1}^{y*}}] = \sigma_{sy}^2 \geq 0$ . These net bond supplies should be viewed as the gross supply of long-term bonds *minus* the demand of any inelastic “preferred habitat” investors—i.e., they reflect the combined supply and demand shocks that global bond investors must absorb in equilibrium.<sup>13</sup>

**Net FX supply** We assume that global bond investors must engage in a borrow-domestic and lend-foreign FX trade in time-varying market value (in domestic currency units)  $s_t^q$  to accommodate the opposing demand of other unmodeled agents. For example, if nonfinancial firms have an inelastic demand to exchange foreign currency for domestic currency, global bond investors must take the other side, going long foreign currency and short domestic currency. We assume:

$$s_{t+1}^q = \phi_{sq}s_t^q + \varepsilon_{s_{t+1}^q}, \quad (15)$$

where  $Var_t[\varepsilon_{s_{t+1}^q}] = \sigma_{sq}^2 \geq 0$  and  $\phi_{sq} \in [0, 1)$ . Of course, if we consider all agents in the global economy, then foreign exchange must be in zero net supply: if some agent is exchanging dollars for euros, then some other agent must be exchanging euros for dollars. However, the specialized bond investors in our model are only a subset of all actors in global financial markets, so they need not have zero foreign exchange exposure.

Collecting terms, let  $\boldsymbol{\varepsilon}_{t+1} \equiv [\varepsilon_{i_{t+1}}, \varepsilon_{i_{t+1}^*}, \varepsilon_{s_{t+1}^y}, \varepsilon_{s_{t+1}^{y*}}, \varepsilon_{s_{t+1}^q}]'$  and  $\boldsymbol{\Sigma} \equiv Var_t[\boldsymbol{\varepsilon}_{t+1}]$ . For simplicity, we assume the three supply shocks are independent of each other and of both short rates.

### 3.1.3 Global bond investors

The global bond investors in our model are specialized investors who choose portfolios consisting of short-term and long-term bonds in the two currencies. They have mean-variance preferences

<sup>13</sup>The Online Appendix discusses the impact of relaxing these symmetry assumptions on short rates and bond supply.

over next-period wealth with risk tolerance  $\tau$ . Let  $d_t^y$  ( $d_t^{y*}$ ) denote the market value of bond investors' holdings of long-term domestic (foreign) bonds and let  $d_t^q$  denote the value of investors' position in the borrow-domestic and lend-foreign FX trade, all denominated in domestic currency. Thus, defining  $\mathbf{d}_t \equiv [d_t^y, d_t^{y*}, d_t^q]'$  and  $\mathbf{r}\mathbf{x}_{t+1} \equiv [rx_{t+1}^y, rx_{t+1}^{y*}, rx_{t+1}^q]'$ , investors choose their holdings to solve:<sup>14</sup>

$$\max_{\mathbf{d}_t} \left\{ \mathbf{d}_t' E_t [\mathbf{r}\mathbf{x}_{t+1}] - \frac{1}{2\tau} \mathbf{d}_t' Var_t [\mathbf{r}\mathbf{x}_{t+1}] \mathbf{d}_t \right\}, \quad (16)$$

so their demands must satisfy:

$$E_t [\mathbf{r}\mathbf{x}_{t+1}] = \tau^{-1} Var_t [\mathbf{r}\mathbf{x}_{t+1}] \mathbf{d}_t. \quad (17)$$

These preferences are similar to assuming that investors manage their overall risk exposure using Value-at-Risk or other standard risk management techniques.

In practice, we associate the global bond investors in our model with market players such as fixed-income divisions at global broker-dealers and large global macro hedge funds. Relative to more broadly diversified players in global capital markets, risk factors related to movements in interest rates loom large for these imperfectly diversified bond market players. Indeed, the particular form of segmentation that we assume is quite natural since both government bonds and foreign exchange are interest-rate sensitive assets. Any human capital or physical infrastructure that is useful for managing interest-rate sensitive assets can be readily applied to both bonds and foreign exchange.

## 3.2 Equilibrium

### 3.2.1 Conjecture and solution

We need to pin down three equilibrium prices:  $y_t$ ,  $y_t^*$ , and  $q_t$ . To solve the model, we conjecture that prices are linear functions of a  $5 \times 1$  state vector  $\mathbf{z}_t = [i_t, i_t^*, s_t^y, s_t^{y*}, s_t^q]'$ . As shown in the Online Appendix, a rational expectations equilibrium of our model is a fixed point of an operator involving the “price-impact” coefficients which govern how the supplies  $\mathbf{s}_t = [s_t^y, s_t^{y*}, s_t^q]'$  impact  $y_t$ ,  $y_t^*$ , and  $q_t$ . Specifically, the market clearing condition  $\mathbf{d}_t = \mathbf{s}_t$  implicitly defines an operator which gives the expected returns—and, hence, the price-impact coefficients—that will clear markets when investors believe the risk of holding assets is determined by some initial set of price-impact coefficients. A rational expectations equilibrium of our model is a fixed point of this operator.

In the absence of supply risk ( $\sigma_{s_y}^2 = \sigma_{s_q}^2 = 0$ ), this fixed-point problem is degenerate, and

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<sup>14</sup>We assume that global bond investors solve (16) irrespective of whether they are domestic- or foreign-based. We can represent an investor's positions in any asset other than short-term bonds in her local currency as a linear combination of three long-short trades: the yield curve trade in each currency and the FX trade. Therefore, assuming all investors have the same risk tolerance *in domestic currency terms* (i.e., the risk tolerance of any foreign-based investors is  $\tau/Q_t$  in foreign-currency terms) and hold the same beliefs about returns, all global bond investors will choose the same exposures in domestic currency terms to these three long-short trades regardless of where they are based. As a result, since investors can hedge any FX risk stemming from investments in long-term bonds in non-local currency, they will only take on FX exposure if they are rewarded for doing so.

there is a straightforward, unique equilibrium. However, when asset supply is stochastic, the fixed-point problem is non-degenerate: the risk of holding assets depends on how prices react to supply shocks. For example, if investors believe supply shocks will have a large impact on prices, they perceive assets as being highly risky. As a result, investors will only absorb supply shocks if they are compensated by large price declines and high future expected returns, making the initial belief self-fulfilling. This kind of logic means that (i) an equilibrium only exists when investors' risk tolerance  $\tau$  is sufficiently large relative to the volatility of supply shocks and (ii) the model admits multiple equilibria. However, there is at most one equilibrium that is stable in the sense that it is robust to a small perturbation in investors' beliefs regarding equilibrium price impact.<sup>15</sup> We focus on this unique stable equilibrium in our analysis.

### 3.2.2 Equilibrium expected returns and prices

We now characterize equilibrium expected returns and prices. Market clearing implies that  $\mathbf{d}_t = \mathbf{s}_t$ . Thus, using equation (17), equilibrium expected returns must satisfy:

$$E_t[\mathbf{r}\mathbf{x}_{t+1}] = \tau^{-1}Var_t[\mathbf{r}\mathbf{x}_{t+1}]\mathbf{s}_t = \tau^{-1}\mathbf{V}\mathbf{s}_t, \quad (18)$$

where  $\mathbf{V} = Var_t[\mathbf{r}\mathbf{x}_{t+1}]$  is constant in equilibrium. Writing out Eq. (18) and making use of the symmetry between long-term domestic and foreign bonds in equations (13) and (14), we have:

$$E_t[rx_{t+1}^y] = \frac{1}{\tau}[V_y \times s_t^y + C_{y,y^*} \times s_t^{y^*} + C_{y,q} \times s_t^q] \quad (19a)$$

$$E_t[rx_{t+1}^{y^*}] = \frac{1}{\tau}[C_{y^*,y} \times s_t^y + V_y \times s_t^{y^*} - C_{y,q} \times s_t^q] \quad (19b)$$

$$E_t[rx_{t+1}^q] = \frac{1}{\tau}[C_{y,q} \times (s_t^y - s_t^{y^*}) + V_q \times s_t^q], \quad (19c)$$

where  $V_y \equiv Var_t[rx_{t+1}^y] = Var_t[rx_{t+1}^{y^*}]$ ,  $C_{y^*,y} \equiv Cov_t[rx_{t+1}^y, rx_{t+1}^{y^*}]$ , and  $C_{y,q} \equiv Cov_t[rx_{t+1}^y, rx_{t+1}^q] = -Cov_t[rx_{t+1}^{y^*}, rx_{t+1}^q]$ . These variances and covariances are equilibrium objects: they depend both on shocks to short-term interest rates and on the equilibrium price impact of supply shocks.

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<sup>15</sup>Equilibrium non-existence and multiplicity are common in models like ours where short-lived investors absorb shocks to the supply of infinitely-lived assets. Consistent with Samuelson's (1947) "correspondence principle," the unique stable equilibrium has comparative statics that accord with standard intuition. By contrast, the comparative statics of the unstable equilibria are usually counterintuitive. For instance, at an unstable equilibrium, an increase in the volatility of short rate shocks can reduce the impact that supply shocks have on equilibrium prices. By contrast, in the stable equilibrium, an increase in the volatility of short rate shocks always increases the impact of supply shocks on equilibrium prices. For previous treatments of these issues, see De Long, Shleifer, Summers, and Waldmann (1990), Spiegel (1998), Watanabe (2008), Banerjee (2011), Albagli (2015), and Greenwood, Hanson, and Liao (2018).



Making use of Eqs. (10) and (12) and the AR(1) dynamics for  $i_t$ ,  $i_t^*$ ,  $s_t^y$ ,  $s_t^{y*}$ , and  $s_t^q$ , we can then characterize equilibrium yields and the exchange rate. The long-term domestic yield is:

$$y_t = \underbrace{\left\{ \bar{i} + \frac{1-\delta}{1-\delta\phi_i} \times (i_t - \bar{i}) \right\}}_{\text{Expectations hypothesis}} + \underbrace{\left\{ \tau^{-1} (V_y + C_{y,y^*}) \times \bar{s}^y \right\}}_{\text{Steady-state term premium}} + \underbrace{\left\{ \tau^{-1} \frac{1-\delta}{1-\delta\phi_{sy}} [V_y \times (s_t^y - \bar{s}^y) + C_{y,y^*} \times (s_t^{y*} - \bar{s}^y)] + \tau^{-1} \frac{1-\delta}{1-\delta\phi_{sq}} C_{y,q} \times s_t^q \right\}}_{\text{Time-varying term premium}}; \quad (20a)$$

the long-term foreign yield is:

$$y_t^* = \underbrace{\left\{ \bar{i} + \frac{1-\delta}{1-\delta\phi_i} \times (i_t^* - \bar{i}) \right\}}_{\text{Expectations hypothesis}} + \underbrace{\left\{ \tau^{-1} (V_y + C_{y,y^*}) \times \bar{s}^y \right\}}_{\text{Steady-state term premium}} + \underbrace{\left\{ \tau^{-1} \frac{1-\delta}{1-\delta\phi_{sy}} [C_{y,y^*} \times (s_t^y - \bar{s}^y) + V_y \times (s_t^{y*} - \bar{s}^y)] - \tau^{-1} \frac{1-\delta}{1-\delta\phi_{sq}} C_{y,q} \times s_t^q \right\}}_{\text{Time-varying term premium}}; \quad (20b)$$

and the foreign exchange rate is

$$q_t = \underbrace{\left\{ \frac{1}{1-\phi_i} \times (i_t^* - i_t) \right\}}_{\text{Uncovered interest rate parity}} - \underbrace{\left\{ \tau^{-1} \frac{1}{1-\phi_{sy}} C_{y,q} \times (s_t^y - s_t^{y*}) + \tau^{-1} \frac{1}{1-\phi_{sq}} V_q \times s_t^q \right\}}_{\text{FX risk premium}}. \quad (20c)$$

Eqs. (20a) and (20b) say that long-term domestic and foreign yields are the sum of an expectations hypothesis piece that reflects expected future short-term rates and a term premium piece that reflects expected future bond risk premia. The expectations hypothesis component for domestic long-term bonds, for example, depends on the current deviation of short-term domestic rates from their steady-state level ( $i_t - \bar{i}$ ) and the persistence of short-term rates ( $\phi_i$ ). Similarly, the domestic term premium depends on the current deviation of asset supplies from their steady state levels and the persistence of those asset supplies. Eq. (20c) says that the foreign exchange rate consists of a UIP term, reflecting expected future foreign-minus-domestic short rate differentials, minus a risk-premium term that reflects expected future excess returns on the borrow-domestic lend-foreign FX trade.

### 3.2.3 Understanding equilibrium expected returns

We can understand expected returns in terms of exposures to the five risk factors in our model. Formally, the time- $t$  conditional expected return on any asset  $a \in \{y, y^*, q\}$  satisfies:

$$E_t[rx_{t+1}^a] = \beta_i^a \lambda_{i,t} + \beta_{i^*}^a \lambda_{i^*,t} + \beta_{s^y}^a \lambda_{s^y,t} + \beta_{s^{y^*}}^a \lambda_{s^{y^*},t} + \beta_{s^q}^a \lambda_{s^q,t}, \quad (21)$$

where, for factors  $f \in \{i, i^*, s^y, s^{y^*}, s^q\}$ ,  $\beta_f^a$  is the constant loading of asset  $a$ 's returns on factor innovation  $\varepsilon_{f,t+1}$  and  $\lambda_{f,t}$  is the time-varying equilibrium price of bearing  $\varepsilon_{f,t+1}$  risk. Formally,  $\beta_f^a$

is the coefficient on  $\varepsilon_{f_{t+1}}$  from a multivariate regression of  $-(rx_{t+1}^a - E_t[rx_{t+1}^a])$  on the innovations to the five risk factors. For instance, long-term domestic bonds have a positive loading on  $\varepsilon_{i_{t+1}}$  and no loading on  $\varepsilon_{i_{t+1}^*}$ . At time  $t$ , the prices of domestic and foreign short-rate risk are:

$$\lambda_{i,t} = \tau^{-1}\sigma_i^2 \times \sum_a [(\beta_i^a + \rho\beta_{i^*}^a) \times s_t^a], \quad (22a)$$

$$\lambda_{i^*,t} = \tau^{-1}\sigma_i^2 \times \sum_a [(\rho\beta_i^a + \beta_{i^*}^a) \times s_t^a], \quad (22b)$$

and, for  $f \in \{s^y, s^{y^*}, s^q\}$ , the prices of supply risk are:

$$\lambda_{f,t} = \tau^{-1}\sigma_f^2 \times \sum_a [\beta_f^a \times s_t^a]. \quad (22c)$$

The prices of risk all depend on asset supply quantities due to the limited risk tolerance of global bond investors.

Expected returns can also be written using a “conditional-CAPM” representation. Letting  $rx_{t+1}^{st} = \mathbf{s}'_t \mathbf{r}\mathbf{x}_{t+1}$  denote the excess return on global bond investors’ portfolio from  $t$  to  $t + 1$ , the conditional expected return on any risky asset  $a \in \{y, y^*, q\}$  is:

$$E_t[rx_{t+1}^a] = \frac{Cov_t[rx_{t+1}^a, rx_{t+1}^{st}]}{Var_t[rx_{t+1}^{st}]} \times E_t[rx_{t+1}^{st}]. \quad (23)$$

The expected return on each asset equals its conditional  $\beta$  with respect to the portfolio held by bond investors times the conditional expected return on that portfolio. Relatedly, the stochastic discount factor (SDF) that prices risky assets—i.e., the random variable  $m_{t+1}$  that satisfies  $E_t[rx_{t+1}^a] = -Cov_t[rx_{t+1}^a, m_{t+1}]$  for all  $a$ —is  $m_{t+1} = -\tau^{-1}rx_{t+1}^{st}$ . In other words, “bad times” in our model—states of the world where  $m_{t+1}$  is high—are states where the excess return on global bond investors’ portfolio ( $rx_{t+1}^{st}$ ) is low.

Eq. (23) is superficially similar to the pricing condition that would obtain if the true conditional-CAPM held in fully-integrated global capital markets. However, in our model, the portfolio return that prices risky assets is the return on the portfolio held by specialized bond investors. By contrast, in fully integrated markets, the portfolio return that prices all financial assets is the market portfolio consisting of all global financial wealth.

### 3.3 Bond term premia and exchange rates

The major payoff from our baseline model is that we are able to study the simultaneous determination of domestic term premia, foreign term premia, and foreign exchange risk premia. Specifically, we can ask how a shift in the supply on any of these three assets impacts the equilibrium expected returns on the two other assets using Eq. (19).

### 3.3.1 Limiting case with no supply risk

Many of the core results of the model can be illustrated using the limiting case in which asset supplies are constant over time, leaving only short rate risk—i.e., where  $\sigma_{sy}^2 = \sigma_{sq}^2 = 0$ .<sup>16</sup>

**Proposition 1** *Equilibrium without supply shocks.* *If  $\sigma_{sy}^2 = \sigma_{sq}^2 = 0$  and  $\rho \in (0, 1)$ , then*

$$V_y = \left( \frac{\delta}{1 - \delta\phi_i} \right)^2 \sigma_i^2 > 0 \text{ and } V_q = 2 \left( \frac{1}{1 - \phi_i} \right)^2 (1 - \rho) \sigma_i^2 > 0, \quad (24)$$

$$C_{y,y^*} = \rho \left( \frac{\delta}{1 - \delta\phi_i} \right)^2 \sigma_i^2 > 0 \text{ and } C_{y,q} = (1 - \rho) \frac{\delta}{1 - \delta\phi_i} \frac{1}{1 - \phi_i} \sigma_i^2 > 0. \quad (25)$$

Thus,  $\partial E_t[r x_{t+1}^q] / \partial s_t^y = \tau^{-1} C_{y,q}$  is decreasing in the correlation between domestic and foreign short rates,  $\rho$ , whereas  $\partial E_t[r x_{t+1}^{y^*}] / \partial s_t^y = \tau^{-1} C_{y,y^*}$  is increasing in  $\rho$ .

**Proof.** All proofs are in the Online Appendix, which is available here. ■

Proposition 1 provides guidance about how shifts in long-term bond supply—e.g., due to QE policies—should impact exchange rates and term premia. There are two key takeaways.

First, Proposition 1 shows that a shift in domestic bond supply impacts the domestic term premium, the foreign term premium, and the FX risk premium. For example, suppose there is an increase in the supply of dollar long-term bonds. This increase in dollar bond supply raises the price of bearing dollar short-rate risk in Eq. (22a), lifting the expected returns on the dollar yield curve trade and thus dollar long-term yields as in Vayanos and Vila (2019). The increase in dollar bond supply also raises the euro term premium and euro long-term yields when dollar and euro short rates are correlated ( $\rho > 0$ ). Turning to exchange rates, Eq. (20c) shows that the borrow-in-dollars to lend-in-euros FX trade is also exposed to dollar short-rate risk: the euro depreciates when dollar short rates rise through the standard UIP channel. Because the price of bearing dollar short-rate rises following an increase in the supply of dollar long-term bonds, the expected returns on the FX trade must also rise. Thus, an increase in the supply of long-term dollar bonds leads the euro to depreciate; it is then expected to appreciate going forward.<sup>17</sup>

Second, Proposition 1 shows that the effects of a shift in domestic bond supply depend on the correlation  $\rho$  between domestic and foreign short-rates. When  $\rho$  is higher, more of the effect of the domestic bond supply shift appears in long-term foreign yields and less shows up in the exchange rate. For instance, U.S. short-term rates are more highly correlated with euro short rates than with Japanese yen short rates. Thus, Proposition 1 suggests we should expect U.S. QE—a reduction in dollar bond supply—to lead to a larger depreciation of the dollar versus the yen than versus the euro. At the same time, U.S. QE should lead to a larger reduction in euro

<sup>16</sup>Technically, the comparative statics in Proposition 1 must be interpreted as comparative statics on the steady-state level of expected returns across economies where asset supplies are constant over time—i.e., they give the effects of supply shifts that investors think are impossible. Nevertheless, the limiting case without supply risk highlights the core mechanism at the heart of our model.

<sup>17</sup>More precisely, when  $\rho > 0$ , an increase in the supply of long-term dollar bonds raises the prices of both dollar and euro short-rate risk per Eqs. (22a) and (22b). As shown in Eq. (20c), the FX trade has offsetting exposures to dollar and euro short rates due to standard UIP logic. However, when the two short rate processes are symmetric as in Eq. (13), the exposure to dollar short rates dominates and we have  $\partial E_t[r x_{t+1}^q] / \partial s_t^y > 0$ .

term premia than yen term premia. Intuitively, if foreign and domestic short rates are highly correlated, the UIP component of the exchange rate will not be very volatile; if domestic short rates rise, foreign short rates are also likely to rise, leaving the UIP component of the exchange rate largely unchanged. This means that the FX trade is not very exposed to interest rate risk and, therefore, its expected return should not move much in response to bond supply shifts.

Corollary 1 details the limiting case where  $\delta \rightarrow 1$ , and therefore the duration of long-term bonds  $D = 1/(1 - \delta)$  goes to infinity.

**Corollary 1** *Limit where the duration of long-term bonds becomes infinite.* Suppose  $\sigma_{sy}^2 = \sigma_{sq}^2 = 0$  and consider the limit where  $\delta \rightarrow 1$ . In this limit, we have

$$V_y = \left( \frac{1}{1 - \phi_i} \right)^2 \sigma_i^2 > 0, V_q = 2(1 - \rho)V_y, C_{y,y^*} = \rho V_y, \text{ and } C_{y,q} = (1 - \rho)V_y, \quad (26)$$

so  $\text{Var}_t [rx_{t+1}^q + (rx_{t+1}^{y^*} - rx_{t+1}^y)] = V_q + 2V_y - 2C_{y,y^*} - 4C_{y,q} = 0$ —i.e., the long-term FX carry trade is riskless. Thus, long-term UIP must hold state-by-state and hence also in expectation (i.e.,  $rx_{t+1}^q + (rx_{t+1}^{y^*} - rx_{t+1}^y) = E_t [rx_{t+1}^q + (rx_{t+1}^{y^*} - rx_{t+1}^y)] = 0$ ). As a result,  $\partial E_t[rx_{t+1}^y]/\partial s_t^y = \tau^{-1}V_y$  equals the sum of  $\partial E_t[rx_{t+1}^{y^*}]/\partial s_t^y = \tau^{-1}\rho V_y$  and  $\partial E_t[rx_{t+1}^q]/\partial s_t^y = \tau^{-1}(1 - \rho)V_y$ .

In the  $\delta \rightarrow 1$  limit where the duration of long-term bonds becomes infinite, the long-term FX carry trade that borrows long-term in dollars and lends long-term in euros becomes riskless. As a result, the return on the long-term carry trade must be zero by the absence of arbitrage—i.e., we must have  $\lim_{\delta \rightarrow 1} [rx_{t+1}^q + (rx_{t+1}^{y^*} - rx_{t+1}^y)] = 0$  state-by-state.<sup>18</sup> Even though long-term UIP holds in this limit, our model still pins down precise *mix* of equilibrium adjustments that ensure it holds following a change in asset supply. For instance, suppose there is an increase in dollar bond supply  $s_t^y$ . This bond supply shock raises the term premium on long-term U.S. bonds,  $E_t[rx_{t+1}^y]$ . Long-term UIP implies that some combination of the term premium on Euro bonds ( $E_t[rx_{t+1}^{y^*}]$ ) and the FX premium ( $E_t[rx_{t+1}^q]$ ) must adjust in response. What Corollary 1 shows is that the correlation between domestic and foreign short rates,  $\rho$ , governs whether the adjustment comes through the foreign term premium or the FX risk premium. Specifically, when the correlation  $\rho$  is higher, more of the adjustment comes through a rise in the foreign term premium and less comes through a rise in the FX premium.

### 3.3.2 Adding supply shocks

We now show that these results generalize once we add stochastic shocks to the net supplies of domestic and foreign long-term bonds and to foreign exchange.<sup>19</sup>

<sup>18</sup>The fact that  $\lim_{\delta \rightarrow 1} \text{Var}_t [rx_{t+1}^q + (rx_{t+1}^{y^*} - rx_{t+1}^y)] = \lim_{\delta \rightarrow 1} E_t [rx_{t+1}^q + (rx_{t+1}^{y^*} - rx_{t+1}^y)] = 0$  continues to hold once we introduce stochastic supply shocks below. However, whether or not supply is stochastic, the long-term FX carry trade remains exposed to interest rate risk when  $\delta < 1$  and long-term bonds have finite durations. As a result, long-term UIP fails in our model when  $\delta < 1$ .

<sup>19</sup>As shown in the Online Appendix, when  $\sigma_{sy}^2 > 0$  and  $\sigma_{sq}^2 > 0$ , solving the model involves characterizing the stable solution to a system of four quadratic equations in four unknowns. When  $\sigma_{sy}^2 > 0$  and  $\sigma_{sq}^2 = 0$ , the model can be solved analytically: we simply need to solve two quadratics and a linear equation.

**Proposition 2 *Equilibrium with supply shocks.*** *If  $0 \leq \rho < 1$ ,  $\sigma_{s_y}^2 \geq 0$ ,  $\sigma_{s_q}^2 \geq 0$ , then in any stable equilibrium we have  $\partial E_t[r x_{t+1}^q] / \partial s_t^y = \tau^{-1} C_{y,q} > 0$ . If in addition  $\rho > 0$  and  $\sigma_{s_q}^2 = 0$ , then in any stable equilibrium we have  $\partial E_t[r x_{t+1}^{y*}] / \partial s_t^y = \tau^{-1} C_{y,y*} > 0$ . Thus, by continuity of the stable equilibrium in the model's underlying parameters, we have  $\partial E_t[r x_{t+1}^{y*}] / \partial s_t^y > 0$  unless foreign exchange supply shocks are especially volatile and  $\rho$  is near zero.*

Proposition 2 shows that, once we allow supply to be stochastic, shifts in bond supply continue to impact bond yields and foreign exchange rates as they did in Proposition 1 where supply was fixed. Shifts in supply tend to amplify the comovement between long-term bonds and foreign exchange that is attributable to shifts in short-term interest rates.

The exception is when FX supply shocks are especially volatile ( $\sigma_{s_q}^2$  is large) and the correlation of short rates  $\rho$  is low. Because FX supply shocks push domestic and foreign long-term yields in opposite directions by Eq. (20), if these shocks are highly volatile they can result in a negative equilibrium correlation between domestic and foreign bond returns,  $C_{y,y*}$ , even if the underlying short rates are positively correlated. However, in the empirically relevant case where  $\rho$  is meaningfully positive, we have  $C_{y,y*} > 0$  and bond yields behave as in Proposition 1.

### 3.3.3 Empirical implications of the baseline model

In Section 2, we presented evidence for three propositions. First, exchange rates appear to be about as sensitive to changes in long-term interest rate differentials as they are to changes in short-term interest rate differentials. Second, the component of long rate differentials that matters for exchange rates appears to be a term premium differential. Third, the term premium differentials that move exchange rates appear to be, at least in part, quantity-driven. Using our baseline model, we can now formally motivate these empirical results.

For simplicity, we focus on the case where FX supply shocks are small—i.e., the limit where  $s_t^q = 0$  and  $\sigma_{s_q}^2 = 0$ .<sup>20</sup> In this case, the foreign exchange risk premium is decreasing in the difference between foreign and domestic bond supply ( $s_t^{y*} - s_t^y$ ),

$$E_t [r x_{t+1}^q] = \overbrace{[-\tau^{-1} C_{y,q}]^{<0}} \times (s_t^{y*} - s_t^y), \quad (27)$$

and the difference between foreign and domestic bond risk premia is increasing in  $s_t^{y*} - s_t^y$ :

$$E_t [r x_{t+1}^{y*} - r x_{t+1}^y] = \overbrace{[\tau^{-1} (V_y - C_{y,y*})]^{>0}} \times (s_t^{y*} - s_t^y). \quad (28)$$

Eqs. (27) and (28) motivate our regressions examining QE announcement dates in Section 2. In the context of the model, we think of a euro QE announcement as news indicating that the supply of euro long-term bonds  $s_t^{y*}$  will be low. Eq. (28) shows that this decline in euro bond supply should reduce euro term premia relative to dollar term premia. And, Eq. (27) shows that this decline in  $s_t^{y*}$  should increase the risk premium on the borrow-in-dollar lend-in-euros FX trade,

<sup>20</sup>The Online Appendix shows that a similar set of results obtains when  $\sigma_{s_q}^2 > 0$  and  $s_t^q \neq 0$ .

leading the euro to depreciate relative to the dollar. By symmetry, U.S. QE announcements—i.e., news that  $s_t^y$  will be low—will have the opposite effects.

Combining Eqs. (27) and (28), the FX risk premium is negatively related to the difference between foreign and domestic bond term premia:

$$E_t [rx_{t+1}^q] = \overbrace{\left[ -\frac{C_{y,q}}{V_y - C_{y,y^*}} \right]}^{<-1} \times E_t [rx_{t+1}^{y^*} - rx_{t+1}^y]. \quad (29)$$

Eq. (29) motivates Table 4 in Section 2 where we forecast foreign exchange returns using the difference in (proxies for) foreign and domestic term premia. When euro bond supply is high, the euro term premium is high and the risk premium on the borrow-in-dollars lend-in-euros FX trade is low. Thus, the FX risk premium moves inversely with the foreign term premium. The same argument applies to the domestic term premium with the opposite sign—the FX risk premium moves proportionately with the domestic term premium.<sup>21</sup>

Combining Eq. (12) and (29), the exchange rate reflects the sum of expected (i) foreign-minus-domestic short rate differentials and (ii) foreign-minus-domestic bond risk-premium differentials:

$$q_t = \sum_{j=0}^{\infty} E_t [i_{t+j}^* - i_{t+j}] + \overbrace{\left[ \frac{C_{y,q}}{V_y - C_{y,y^*}} \right]}^{>1} \times \sum_{j=0}^{\infty} E_t [rx_{t+j+1}^{y^*} - rx_{t+j+1}^y]. \quad (30)$$

This result motivates Tables 1 and 2 where we regress changes in exchange rates on changes in short rate differentials and changes in (proxies for) term premium differentials. When foreign bond supply is high, the foreign term premium is high and the risk premium on the borrow-at-home to lend-abroad FX trade is low. For investors to earn low returns on foreign currency, foreign currency must be strong— $q_t$  must be high—and must be expected to depreciate.<sup>22</sup>

Lastly, our model can match the otherwise puzzling finding in Lustig, Stathopoulos, and Verdelhan (2019) that the return to the FX trade—conventionally implemented by borrowing and lending short-term in different currencies—declines if one borrows long-term and lends long-term.<sup>23</sup> To see this, note that the return on a long-term FX trade that borrows long-term at

<sup>21</sup>The constant of proportionality in Eq. (29),  $-C_{y,q}/(V_y - C_{y,y^*})$ , is less than  $-1$  because foreign exchange is effectively a “longer duration” asset than long-term bonds when  $\delta < 1$ .

<sup>22</sup>An alternative interpretation is that our results on long-term yields and foreign exchange rates reflect movements in convenience premia, as in Krishnamurthy and Vissing-Jorgensen (2012) and Jiang, Krishnamurthy, and Lustig (2019). Convenience premia are also quantity-driven, but are conceptually distinct from the bond term premia that are our focus. Fluctuations in convenience premia should generate the opposite relationship between contemporaneous changes in foreign exchange rates and U.S. Treasury yields. Suppose there is an increase in the supply of U.S. Treasury debt and the demand for Treasuries is downward sloping. Then the convenience premium falls, pushing up Treasury yields. If foreign investors derive greater convenience services from Treasuries than do U.S. investors, this increase in supply should also lead foreign currencies should appreciate versus the dollar. Thus, movements in the convenience premium should lead to a positive correlation between Treasury yields and movements in foreign currencies. In untabulated results, we control for the innovation to U.S. Treasury basis as constructed by Jiang, Krishnamurthy, and Lustig (2019) and find that the coefficients of interest in Tables 1 and 2 are essentially unchanged.

<sup>23</sup>The Lustig, Stathopoulos, and Verdelhan (2019) result is closely related to the finding in Meredith and Chinn (2004) that long-horizon, hold-to-maturity FX carry trades earn much lower returns than the traditional

home to lend long-term abroad is just a combination of our three long-short returns. Specifically, the return on this long-term FX trade equals (i) the return to borrowing long to lend short domestically ( $-rx_{t+1}^y$ ), plus (ii) the return to borrowing short domestically to lend short in the foreign currency ( $rx_{t+1}^q$ ), plus (iii) the return to borrowing short to lend long in the foreign currency ( $rx_{t+1}^{y*}$ ). Thus, the expected return on the long-term FX trade is:

$$E_t [rx_{t+1}^q + (rx_{t+1}^{y*} - rx_{t+1}^y)] = \overbrace{\left[1 - \frac{V_y - C_{y,y^*}}{C_{y,q}}\right]}^{\in(0,1)} \times E_t [rx_{t+1}^q]. \quad (31)$$

Eq. (31) shows that the expected return on the long-term FX trade is smaller in absolute magnitude—and hence less volatile over time—than that on the standard short-term FX trade. The intuition is that the long-term FX trade has offsetting exposures that reduce its riskiness for global bond investors as compared to the standard FX trade. For instance, the standard FX trade ( $rx_{t+1}^q$ ) will suffer when there is an unexpected increase in domestic short rates. However, borrowing long to lend short in domestic currency (i.e.,  $-rx_{t+1}^y$ ) will profit when there is an unexpected rise in domestic short rates. Thus, the long-term FX trade is less exposed to interest rate risk than the standard short-term FX trade. As a result, the expected return on the long-term FX trade moves less than one-for-one with the return on the standard short-term FX trade.

We collect these observations in the following proposition:

**Proposition 3 *Empirical implications.*** *Suppose  $\rho \in [0, 1)$ ,  $\sigma_{s_y}^2 > 0$ , and  $\sigma_{s_q}^2 = 0$ . Then:*

- *The FX risk premium ( $E_t [rx_{t+1}^q]$ ) is decreasing in the difference in net long-term bond supply between foreign and domestic currency ( $s_t^{y^*} - s_t^y$ ). The difference between foreign and domestic bond risk premia,  $E_t [rx_{t+1}^{y^*} - rx_{t+1}^y]$ , is increasing in  $s_t^{y^*} - s_t^y$ .*
- *$E_t [rx_{t+1}^q]$  is negatively related to  $E_t [rx_{t+1}^{y^*} - rx_{t+1}^y]$ .*
- *The foreign exchange rate ( $q_t$ ) is the sum of expected future foreign-minus-domestic short-rate differentials and a term that is proportional to expected future foreign-minus-domestic bond risk premium differentials.*
- *The expected return on the borrow-long-in-domestic to lend-long-in-foreign FX trade ( $E_t [rx_{t+1}^q + (rx_{t+1}^{y^*} - rx_{t+1}^y)]$ ) is smaller in magnitude than that on the standard borrow-short-in-domestic to lend-short-in-foreign FX trade, ( $E_t [rx_{t+1}^q]$ ).*

### 3.4 A unified approach to carry trade returns

In this subsection, we show that our model can deliver a unified explanation that links return predictability in foreign exchange and long-term bond markets to the *levels* of domestic and foreign short-term interest rates. For foreign exchange, Fama (1984) showed that the expected return on the borrow-domestic to lend-foreign FX trade is increasing in the foreign-minus-domestic short

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short-horizon trade.

rate differential,  $i_t^* - i_t$ , a well-known and empirically robust failure of UIP. For long-term bonds, Fama and Bliss (1987) and Campbell and Shiller (1991) showed that the expected return on the borrow-short to lend-long yield curve trade is increasing in the slope of the yield curve,  $y_t - i_t$ , a well-known and empirically robust failure of the expectations hypothesis of the term structure.

The baseline model we developed above does not generate either predictability result. In our baseline model, shocks to short-term interest rates make foreign exchange and long-term bonds risky investments for global bond investors. As a result, supply shocks impact the expected returns on foreign exchange and long-term bonds. However, the levels of domestic and foreign short-term interest rates do not affect the expected excess returns on FX and long-term bonds.

However, a simple extension of our model can simultaneously match these two facts if we follow Gabaix and Maggiori (2015) and, appealing to balance-of-trade flows, assume that global bond investors' exposure to foreign currency is increasing in the strength of the foreign currency. Put simply, our model makes it possible to “kill two birds with one stone.” Specifically, the assumption that Gabaix and Maggiori (2015) need to make to match the Fama (1984) pattern in their model, immediately delivers the Campbell-Shiller (1991) result for both the domestic and foreign yield-curve trades in our model. Symmetrically, the assumption that Vayanos and Vila (2019) need to make to match the Campbell-Shiller (1991) fact in their model—that the net supply of long-term bonds is decreasing in the level of long-term yields—immediately delivers the Fama (1984) pattern for foreign exchange in our model.

Concretely, we extend the model by allowing the net supplies to depend on equilibrium prices:

$$n_t^y = s_t^y - S_y y_t, \quad (32a)$$

$$n_t^{y^*} = s_t^{y^*} - S_y y_t^*, \quad (32b)$$

$$n_t^q = s_t^q + S_q q_t, \quad (32c)$$

where  $S_q, S_y \geq 0$ . That is, we assume the net supply of each asset is increasing that asset's price. For example, the assumption that  $S_q > 0$  follows Gabaix and Maggiori (2015) and is a reduced-form way of modeling balance-of-trade flows in the FX market. Specifically, assume that when foreign currency is strong, domestic exports rise and imports fall, so the domestic country runs a trade surplus of  $S_q q_t$  with the foreign country: If the domestic country is running a trade surplus, domestic exporters will want to swap the foreign currency they receive from their foreign sales for domestic currency. By FX market clearing, global bond investors must take the other side of these trade-driven flows. Thus, when foreign currency is strong, the expected returns on foreign exchange must rise to induce global bond investors to increase their exposure to foreign currency, delivering the Fama (1984) result as Gabaix and Maggiori (2015) show.

Proposition 4 describes the new results.

**Proposition 4** *Matching Fama (1984), Campbell-Shiller (1991), and Lustig, Stathopoulos, and Verdelhan (2019).* Suppose  $\rho \in [0, 1)$ . If (i.a)  $S_q > 0$  and  $S_y = 0$  or (i.b)  $S_q = 0$  and  $S_y > 0$  and (ii) there are no independent supply shocks ( $\sigma_{s_y}^2 = \sigma_{s_q}^2 = 0$ ), then  $\partial E_t [rx_{t+1}^q] / \partial i_t^* = -\partial E_t [rx_{t+1}^q] / \partial i_t > 0$ . Since exchange rates are less responsive to short rates than under UIP,



if one estimates the time-series regression:

$$rx_{t+1}^q = \alpha_q + \beta_q \times (i_t^* - i_t) + \xi_{t+1}^q, \quad (33)$$

one obtains  $\beta_q = \partial E_t[rx_{t+1}^q] / \partial i_t^* > 0$  as in Fama (1984).

Under the same conditions, we also have  $\partial E_t[rx_{t+1}^y] / \partial i_t = \partial E_t[rx_{t+1}^{y*}] / \partial i_t^* < 0$ . Thus, long-term yields are less responsive to movements in short rates than under the expectations hypothesis, so expected returns on long-term bonds are high when short rates are low. Furthermore, since the term spread is high when short rates are low, if one estimates the time-series regressions:

$$rx_{t+1}^y = \alpha_y + \beta_y \times (y_t - i_t) + \xi_{t+1}^y \quad \text{and} \quad rx_{t+1}^{y*} = \alpha_{y^*} + \beta_{y^*} \times (y_t^* - i_t^*) + \xi_{t+1}^{y^*}, \quad (34)$$

one obtains  $\beta_y = \beta_{y^*} > 0$  as in Campbell and Shiller (1991).

Finally, if one estimates the following time-series regression:

$$rx_{t+1}^q + (rx_{t+1}^{y*} - rx_{t+1}^y) = \alpha_{q,lt} + \beta_{q,lt} \times (i_t^* - i_t) + \xi_{t+1}^{q,lt}, \quad (35)$$

one obtains  $0 < \beta_{q,lt} < \beta_q$  as in Lustig, Stathopoulos, and Verdelhan (2019). In other words, the long-term FX carry trade is less profitable than the short-term FX carry trade.

To see the logic, assume  $\sigma_{s^y}^2 = \sigma_{s^q}^2 = 0$ —i.e., there are no independent supply shocks, so net supplies only fluctuate because of movements in short-rates. In this case, we have

$$E_t[rx_{t+1}^q] = \tau^{-1} [C_{y,q} S_y \times (y_t^* - y_t) + V_q \times S_q q_t], \quad (36)$$

and

$$E_t[rx_{t+1}^y - rx_{t+1}^{y*}] = \tau^{-1} [(V_y - C_{y^*,y}) S_y \times (y_t^* - y_t) + 2C_{y,q} S_q \times q_t]. \quad (37)$$

First, assume  $S_q > 0$  and  $S_y = 0$  and suppose that  $i_t^* - i_t > 0$ —i.e., euro short rates exceed dollar short rates. By standard UIP logic, the positive short-rate differential means the euro will be strong—i.e.,  $q_t$  will be high. The assumption that  $S_q > 0$  implies that global bond investors must bear greater exposure to the euro when the euro is strong, raising the expected returns on the borrow-in-dollars lend-in-euros FX trade. As a result, the expected return on the FX trade is increasing in the euro-minus-dollar short-rate differential as in Fama (1984). However, because these FX exposures mean that global bond investors will lose money if dollar short rates rise, the expected return on the dollar yield curve trade must also rise. Since the U.S. term structure will steeper when  $i_t^* - i_t > 0$  by standard expectations-hypothesis logic, the extended model will also match Campbell and Shiller's (1991) finding that a steep yield curve predicts high excess returns on long-term bonds. Finally, due to the negative relationship between the short-term interest rate and the bond term premium in each currency, the model delivers Lustig, Stathopoulos, and Verdelhan's (2019) finding that the returns on the FX carry trade are lower when borrowing long-term in currencies with low interest rates to lend long-term in currencies with high rates.<sup>24</sup>

<sup>24</sup>Indeed,  $\lim_{\delta \rightarrow 1} \beta_{q,lt} = 0$ . Specifically, as shown above,  $rx_{t+1}^q + (rx_{t+1}^{y*} - rx_{t+1}^y)$  converges to zero state-by-

Another way to simultaneously match these two facts within our model is to follow Vayanos and Vila (2019) and assume the net supply of long-term bonds is decreasing in the level of long-term yields—i.e., to assume that  $S_y > 0$ . This would be the case if, as in the data, firms and governments tend to borrow long-term when the level of interest rates is low, or if there are “yield-oriented investors” who tend substitute away from long-term bonds and towards equities when interest rates are low. As Vayanos and Vila (2019) show, assuming  $S_y > 0$  delivers the Campbell-Shiller (1991) result for long-term bonds. Specifically, assume  $S_y > 0$  and  $S_q = 0$  and suppose that  $i_t^* - i_t > 0$ . By standard expectations hypothesis logic, euro long-term rates will be higher than dollar long-term rates, but the yield curve will be steeper in dollars since dollar short rates will be expected to rise more over time. However, since the net supply of long-term bonds is decreasing in long-term yields, the net supply of dollar long-term bonds will be higher than the supply of euro long-term bonds. This means the term premium component of long-term yields will be larger in dollars than in euros, matching Campbell-Shiller (1991). In addition, since global bond investors will have a larger exposure to dollar short-rate shocks, the expected return on the FX trade will also be positive. As a result, the expected return on the FX trade will be increasing in the difference between euro and dollar short-term rates, matching the Fama (1984) pattern.

Finally, once we link supply to prices, changes in conventional monetary policy in the eurozone ( $i_t^*$ ) impact U.S. term premia ( $E_t [rx_{t+1}^y]$ ) and vice versa, meaning the Friedman-Obstfeld-Taylor trilemma fails. In the absence of capital controls, foreign monetary policy impacts domestic financial conditions despite floating exchanges rates. The sign of this effect is ambiguous and depends on  $S_q$ ,  $S_y$ , and  $\rho$ . Specifically, we have the following result:

**Proposition 5 *Impact of foreign short rates on domestic term premia and vice versa.***

Suppose  $\sigma_{s^y}^2 = \sigma_{s^q}^2 = 0$ . (i) If  $S_q > 0$ ,  $S_y = 0$ , and  $\rho \in [0, 1)$ ,  $\partial E_t [rx_{t+1}^y] / \partial i_t^* = \partial E_t [rx_{t+1}^{y*}] / \partial i_t > 0$ . (ii) If  $S_q = 0$ ,  $S_y > 0$ , and  $\rho \in (0, 1]$ ,  $\partial E_t [rx_{t+1}^y] / \partial i_t^* = \partial E_t [rx_{t+1}^{y*}] / \partial i_t < 0$ .

When  $S_q > 0$ ,  $S_y = 0$ , and  $\rho < 1$ , raising foreign short rates raises the domestic term premium. To understand the intuition, suppose that  $i_t^*$  rises—i.e., the ECB tightens monetary policy. This results in an appreciation of the euro relative to the dollar (i.e.,  $q_t$  rises) for UIP reasons. Since  $S_q > 0$  and  $S_y = 0$ , this appreciation in turn raises global bond investors’ exposure to the borrow-in-dollars lend-in-euros trade, which raises their exposure to U.S. short rate risk. Thus, the term premium on long-term U.S. bonds,  $E_t [rx_{t+1}^y]$ , must rise in equilibrium.

By contrast, if  $S_q = 0$ ,  $S_y > 0$ , and  $\rho > 0$ , raising foreign short rates lowers the domestic term premium. Suppose again that short-term euro rates  $i_t^*$  rise. This raises long-term euro yields  $y_t^*$  and *reduces* the supply of long-term euro bonds. Since excess returns on long-term U.S. bonds are positively correlated with the those on long-term euro bonds when  $\rho > 0$ , the term premium on long-term U.S. bonds must decline (i.e.,  $E_t [rx_{t+1}^y]$  must fall).

More generally, when  $S_q > 0$  and  $S_y > 0$ , the sign of  $\partial E_t [rx_{t+1}^y] / \partial i_t^* = \partial E_t [rx_{t+1}^{y*}] / \partial i_t$  is ambiguous and depends on  $S_q$  (increasing  $S_q$  raises  $\partial E_t [rx_{t+1}^y] / \partial i_t^*$  when  $\rho < 1$ ),  $S_y$  (increasing  $S_y$  lowers  $\partial E_t [rx_{t+1}^y] / \partial i_t^*$  when  $\rho > 0$ ), and  $\rho$  (raising  $\rho$  reduces  $\partial E_t [rx_{t+1}^y] / \partial i_t^*$ ).

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state as the duration of long-term bonds approaches infinity ( $\delta \rightarrow 1$ ) and is therefore independent of the short rate differential.

### 3.5 Relationship to consumption-based models

Our quantity-driven, segmented-markets model provides a unified way to understand term premia and exchange rates. Table 6 compares our model’s implications with those of leading frictionless, consumption-based asset pricing models. The table shows that our model is able to simultaneously match many important stylized facts about long-term bonds and foreign exchange rates. By contrast, leading consumption-based models struggle to simultaneously match these empirical patterns in a unified way.

The key driver of the differences is that our assumption that the global bond and foreign exchange markets are partially segmented from financial markets more broadly. As a result, the wealth of intermediaries in these global bond markets need not be closely tied to aggregate consumption or conditions in other financial markets (e.g., equities). To be clear, we are not assuming that financial markets are highly segmented; we are simply positing that there is some segmentation at the level of broad financial asset classes.

As shown in column (1) of Table 6, the starkest implication of this assumption is that, in our model, FX rates move in response to shifts in the supply and demand for assets in different currencies—e.g., central banks’ QE policies—which intermediaries must absorb. By contrast, in frictionless asset-pricing theories, a mere “reshuffling” of assets between different agents in the economy has no asset pricing implications.

A second implication of this segmentation assumption is that “bad times” for the marginal investors in global bond markets need not coincide with “bad times” for more broadly diversified investors or for the representative households in, say, the U.S. and Europe. In particular, while there is a SDF  $M_{t+1}$  that prices risky assets in our model, it is not the case that short-term riskless rates satisfy the usual relationship,  $\exp(-i_t) = E_t[M_{t+1}]$ , with respect to that SDF. As shown in columns (2)-(4) of Table 6, this helps us fit several features of the term structure of interest rates. Empirically, short-term real interest rates typically rise in economic expansions and fall in recessions. As a result, long-term real bonds are a macroeconomic hedge for the representative household, which leads most consumption-based models to predict negative real term premia.<sup>25</sup> Empirically, however, both real term and nominal term premia are positive. By contrast, in our model as in Vayanos and Vila (2019), long-term bonds are risky for specialized bond investors, who suffer capital losses when short rates rise, and real term premia are therefore positive.

Traditional complete-markets models also imply different patterns of comovement between exchange rates and real interest rates than our model, summarized in columns (5)-(7) of Table 6. In complete-markets models, foreign currency appreciates in bad times for foreign agents—i.e.,  $Q_{t+1}/Q_t = M_{t+1}^*/M_{t+1}$  in these models, where  $M_{t+1}^*$  and  $M_{t+1}$  are the foreign and domestic SDF, respectively. This appreciation occurs *despite* the fact that short-term foreign interest rates fall in bad foreign times (Engel [2016]) and makes domestic assets risky for foreign agents, thus rationalizing imperfect international risk sharing with complete financial markets.<sup>26</sup> Furthermore,

<sup>25</sup>There are consumption-based models in which real interest rates rise in recessions, implying a positive real term premium (e.g., Wachter [2006]). Empirically, however, real interest rates tend to fall in recessions.

<sup>26</sup>Lustig and Verdelhan (2019) consider the implications of relaxing the “complete-spanning” assumption that  $\Delta q_{t+1} = m_{t+1}^* - m_{t+1}$  and instead assume  $\Delta q_{t+1} = m_{t+1}^* - m_{t+1} + \eta_{t+1}$  where  $\eta_{t+1}$  is wedge term that captures market incompleteness. If both domestic and foreign agents are both on their Euler equations for short-term

since long-term bonds are hedge assets in consumption-based models, foreign long-term bond yields fall in the same bad foreign times that foreign currency appreciates. As a result, foreign currency returns are positively correlated with long-term foreign bond returns and negatively correlated with long-term domestic bond returns. Thus, in most consumption-based models, the FX risk premium is increasing in the foreign-minus-domestic term premium differential (i.e.,  $E_t[rx_{t+1}^q]$  is positively related to  $E_t[rx_{t+1}^{y*} - rx_{t+1}^y]$ ). See the Online Appendix for additional discussion.

By contrast, in our theory and in the data, foreign currency appreciates when short-term foreign interest rates rise relative to short-term domestic interest rates (Engel [2016]). Furthermore, the realized returns on foreign currency are negatively correlated with foreign bond returns and positively correlated with domestic bond returns. This is because the realized returns on foreign exchange and long-term bonds are both driven by shocks to short-term interest rates. As a result, the expected return on foreign currency is negatively related to the foreign-minus-domestic term premium differential.

As we showed in Section 3.4, our model can also jointly match the Fama (1984) and Campbell-Shiller (1991) forecasting results, thereby linking expected returns to the level of short-term interest rates. While consumption-based models can match the Fama (1984) result (see, e.g., Verdelhan [2010] and Bansal and Shaliastovich [2012]), they struggle to simultaneously match the Campbell-Shiller (1991) pattern, as summarized in columns (8)-(10) of Table 6. Consider, for instance, the habit formation model of Verdelhan (2010). When domestic agents are closer to their habit level of consumption than foreign agents, domestic agents are more risk averse. Thus, the expected excess return to holding foreign currency must be positive at these times. Since the precautionary savings effect dominates the intertemporal substitution effect in Verdelhan’s (2010) model, domestic short rates will be below foreign short rates at these times, thereby generating the Fama (1984) pattern. However, since interest rates decline in bad economic times in the model, long-term real bonds hedge macroeconomic risk and carry a negative term premium. Furthermore, bond risk premia are more negative when short rates are low. Thus, if the Verdelhan (2010) model is calibrated so the term structure is steep when short rates are low, the model delivers a negative association between the term spread and bond risk premia, contrary to Campbell-Shiller (1991). The same is true for Bansal and Shaliastovich (2012), a long-run risks model of foreign exchange.

While it poses a challenge for existing models, it will be possible to develop complete-markets models that, like our model, can match Lustig, Stathopoulos, and Verdelhan’s (2019) finding that the FX carry trade earns lower returns when implemented with long-term bonds instead of short-term bonds. As explained in Lustig et al (2019), the resolution is to assume that the domestic and foreign SDFs share a similar permanent component but different transitory components, implying that international risk-sharing is greater in the long-run. However, to the extent that short- and long-term interest rates still fall in bad times in this next generation of consumption-

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bonds in both currencies, Lustig and Verdelhan (2019) show that this alone imposes tight restrictions on the wedge term  $\eta_{t+1}$ . As a result, while this form of market incompleteness can help explain the volatility of exchange rates and FX risk premium, they show it cannot overturn the crucial (and arguably counterfactual) implication that foreign exchange rates appreciate in bad times for foreign agents.

based models, they will still struggle to match the correlation structure between contemporaneous returns and between different risk premia that we see in the data.

## 4 Deviations from covered-interest-rate parity

In this section, we enrich the structure of intermediation in our model to explore the post-2008 violations of covered interest rate parity (CIP), which have recently been documented by Du, Tepper, and Verdelhan (2018) and Jiang, Krishnamurthy, and Lustig (2019). To do so, we extend the set of intermediaries we consider to include banks. In addition, we introduce 1-period FX forward contracts, which allow period  $t$  investors to lock in an exchange rate for  $t + 1$ . When CIP holds, the “cash” domestic short-term rate equals its “synthetic” counterpart, which is obtained by investing in short-term foreign bonds and hedging the associated FX risk using FX forwards. Since CIP violations imply the existence of riskless profits, unlike deviations from UIP, CIP violations cannot be explained simply by invoking limited investor risk-bearing capacity.

To model deviations from CIP and their connection to other asset prices, we make three changes to the baseline model. First, we split our global bond investors, so half are domiciled in the domestic country and half are domiciled in the foreign country. Second, we assume that the only market participants who can engage in riskless CIP arbitrage trades—i.e., borrowing at the synthetic domestic short rate to lend at the cash domestic short rate—are a set of global banks who face non-risk-based balance sheet constraints. Third, we assume that bond investors must use FX forwards if they want to hedge the currency risk associated with making investments in long-term bonds outside their domiciles. This is equivalent to saying that bond investors cannot directly borrow (i.e., obtain “cash” funding) in non-local currency. They can of course convert their local currency to non-local currency in the spot market and then purchase assets. But if they wish to obtain leverage in non-local currency, they must use “synthetic” funding by transacting in FX forwards. They construct this synthetic funding by borrowing in local currency, converting the proceeds to non-local currency in the spot market, and then forward selling non-local currency in the forward market.

In this setting, we show that deviations from CIP co-move with spot exchange rates as documented in Du, Tepper, and Verdelhan (2018) and Jiang, Krishnamurthy, and Lustig (2019). The intuition is that bond supply shocks generate investor demand to hedge foreign currency risk—or, equivalently, demand for funding in non-local currency—which in turn generates demand for FX forward transactions. When banks accommodate this demand, they engage in riskless CIP arbitrage trades. These trades consume scarce bank balance sheet capacity, so banks are only willing to accommodate FX forward demand if they earn positive profits doing so—i.e., only if there are deviations from CIP.

To illustrate, suppose there is an increase in the supply of long-term domestic bonds. As in our baseline model, this supply shock raises the domestic term premium and the FX risk premium, leading domestic currency to appreciate against foreign. To take advantage of the elevated domestic term premium, foreign bond investors want to buy long-term domestic bonds. They want to do so on an FX-hedged basis to isolate the elevated domestic term premium component

of the investment. This puts pressure on the market for FX forwards, generating deviations from CIP. Equivalently, foreign bond investors want synthetic funding in domestic currency, pushing up the synthetic domestic short rate relative to its cash counterpart. Thus, deviations from CIP are driven by supply-and-demand shocks in the global bond market.

Once we allow for CIP deviations, domestic investors acquire an *endogenous* comparative advantage at absorbing domestic bond supply shocks relative to foreign investors. Intuitively, domestic investors can hold long-term domestic bonds without bearing currency risk or paying the costs of hedging currency risk with FX forwards, while foreign investors cannot.

**Forward foreign exchange rates** Let  $F_t^Q$  denote the 1-period forward exchange rate at time  $t$ :  $F_t^Q$  is the amount of domestic currency per unit of foreign currency that investors can lock in at  $t$  to exchange at  $t + 1$ . Once we introduce forwards, there are two ways to earn a riskless return in domestic currency between  $t$  and  $t + 1$ . First, investors can hold short-term domestic bonds, earning the gross “cash” rate of  $I_t$ . Second, investors can convert domestic currency into  $1/Q_t$  units of foreign currency, invest that foreign currency in short-term foreign bonds at rate  $I_t^*$ , and enter into an forward contract to exchange foreign for domestic currency at  $t + 1$ , obtaining the gross “synthetic” rate of  $F_t^Q I_t^*/Q_t$  units of domestic currency at  $t + 1$ . Under CIP, the cash ( $I_t$ ) and synthetic ( $F_t^Q I_t^*/Q_t$ ) domestic short rates must be equal, implying  $F_t^Q = Q_t I_t/I_t^*$  or  $f_t^q = q_t - (i_t^* - i_t)$  in logs.

By contrast, if CIP fails, the “cross-currency basis”,  $x_t^{cip}$ , given by

$$x_t^{cip} = i_t - (i_t^* + f_t^q - q_t) \quad (38)$$

is nonzero. The cross-currency basis,  $x_t^{cip}$ , is the return on a riskless *CIP arbitrage trade* that borrows short-term in domestic currency on a synthetic basis at rate  $(i_t^* + f_t^q - q_t)$  and lends short-term in domestic currency on a cash basis at rate  $i_t$ . Alternately, we have:

$$f_t^q = q_t - (i_t^* - i_t) - x_t^{cip}. \quad (39)$$

Thus,  $x_t^{cip}$  is positive when the forward FX rate is lower than it would be if CIP held.

**Positions involving FX forwards** We introduce three positions that involve FX forwards:

- *Forward investment in FX*: Consider the excess return in domestic currency on a position in foreign currency that is obtained through a forward purchase of foreign currency. The log excess return on this position is:

$$q_{t+1} - f_t^q = [(q_{t+1} - q_t) + (i_t^* - i_t)] + x_t^{cip} = rx_{t+1}^q + x_t^{cip}, \quad (40)$$

which follows from using the expression for  $f_t^q$  in equation (39) and the fact that  $rx_{t+1}^q \equiv (q_{t+1} - q_t) + (i_t^* - i_t)$ . Thus, a forward investment in foreign currency is equivalent to “stapling” together a standard FX trade, which earns  $rx_{t+1}^q$ , and a long position in the CIP arbitrage trade, which earns  $x_t^{cip}$ . Using FX forwards in this way is a synthetic way

of obtaining funding or leverage for a standard FX trade. An investor in FX uses little or none of their own capital up-front when they use forwards, just as they use little or none of their own capital up-front when they use leverage.

In our baseline model in Section 3 where CIP held, it did not matter where our global bond investors were domiciled. Because bond investors could frictionlessly hedge any exchange rate risk stemming from investments in non-local bonds, we could simply think of investors as picking their exposures to three risky excess returns: on the domestic yield-curve trade, the foreign yield-curve trade, and FX trade. However, once CIP does not hold, it matters where bond investors are domiciled. For instance, fluctuations in the cross-currency basis change the attractiveness of investing in long-term foreign bonds for domestic bond investors because they must either (i) not hedge the FX risk stemming from their foreign bond holdings or (ii) hedge this FX risk at cost  $x_t^{cip}$ . Thus, in this section, we distinguish between foreign and domestic investors when considering FX-hedged investments in non-local long-term bonds:

- *FX-hedged investment in long-term foreign bonds by domestic investors.* To obtain this return from  $t$  to  $t + 1$ , a domestic investor exchanges domestic for foreign currency in the spot market at the time  $t$ , invests that foreign currency in long-term foreign bonds from  $t$  to  $t + 1$ , and then exchanges foreign for domestic currency at  $t + 1$  at the pre-determined forward rate  $F_t^Q$ . The log excess return on this position is approximately:

$$(r_{t+1}^{y*} + f_t^q - q_t) - i_t = rx_{t+1}^{y*} - x_t^{cip}, \quad (41)$$

which follows from using equation (39) and  $rx_{t+1}^{y*} \equiv r_{t+1}^{y*} - i_t^*$ . Thus, an FX-hedged investment in long-term foreign bonds is akin to “stapling” together the foreign yield-curve trade, which earns  $rx_{t+1}^{y*}$ , and a short position in the CIP arbitrage trade, which earns  $-x_t^{cip}$ . Using forwards to hedge FX risk in this way is effectively a way of converting domestic currency funding into foreign currency funding.<sup>27</sup>

- *FX-hedged investment in long-term domestic bonds by foreign investors.* To obtain this return from  $t$  to  $t + 1$ , a foreign investor exchanges foreign for domestic currency in the spot market at the time  $t$ , invests that domestic currency in long-term domestic bonds from  $t$  to  $t + 1$ , and then exchanges domestic for foreign currency at  $t + 1$  at the pre-determined forward rate  $1/F_t^Q$ . The log excess return on this position is approximately:

$$(r_{t+1}^y + q_t - f_t^q) - i_t^* = rx_{t+1}^y + x_t^{cip}. \quad (42)$$

This hedged investment staples together the domestic yield-curve trade, which earns  $rx_{t+1}^y$ , and a long position in the CIP arbitrage trade, which earns  $x_t^{cip}$ .

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<sup>27</sup>FX-hedged positions in foreign risky assets do not completely eliminate the exchange rate risk that investors must bear because the size of the hedge cannot be made contingent on the foreign asset’s subsequent return. Thus, the full FX-hedged return includes a second-order interaction between the local currency excess return on the foreign asset and the excess return on foreign currency. For simplicity, we omit this second-order term—which converges to a constant when investors continuously rebalance their hedges—from our analysis.

**Investor types** We assume half of all bond investors are domiciled in the domestic country and half are domiciled in the foreign country. Both domestic and foreign investors have mean-variance preferences over one-period-ahead wealth and a risk tolerance of  $\tau$  in domestic currency terms.<sup>28</sup> Investors differ only in terms of the returns they can earn because of CIP violations:

1. *Domestic bond investors* are present in mass  $1/2$ . They can obtain a riskless return of  $i_t$  from  $t$  to  $t+1$  by investing in short-term domestic bonds. They can buy long-term domestic bonds, earning an excess return of  $rx_{t+1}^y$ ; they can take FX-hedged positions in long-term foreign bonds, generating an excess return of  $rx_{t+1}^{y*} - x_t^{cip}$ ; and they can make forward investments in foreign currency, earning an excess return of  $rx_{t+1}^q + x_t^{cip}$ . In effect, domestic investors only have access to excess returns  $[rx_{t+1}^y, rx_{t+1}^{y*} - x_t^{cip}, rx_{t+1}^q + x_t^{cip}]'$ . Domestic investors can make *unhedged* investments in long-term foreign bonds—by combining an FX-hedged investment in long-term foreign bonds with a forward investment in foreign currency, they can earn an excess return of  $rx_{t+1}^{y*} + rx_{t+1}^q$ , which is independent of  $x_t^{cip}$ . However, if they want FX-hedged exposure to foreign long-term bonds, they must pay  $x_t^{cip}$ .
2. *Foreign bond investors* are present in mass  $1/2$  and are the mirror image of domestic investors. Foreign investors have access to excess returns  $[rx_{t+1}^y + x_t^{cip}, rx_{t+1}^{y*}, rx_{t+1}^q + x_t^{cip}]'$ .

While domestic and foreign bond investors may transact in FX forwards, they cannot engage in the riskless CIP arbitrage trade in isolation. Specifically, to the extent these bond investors transact in FX forwards, they “staple” together the returns on a riskless CIP arbitrage trade together with those on other risky trades. This assumption is crucial for preventing bond investors, who are risk averse but are not subject to other constraints, from fully arbitraging away deviations from CIP. It is equivalent to assuming that bond investors cannot obtain leverage in non-local currency (i.e., short non-local short-term bonds); they can only obtain synthetic non-local currency funding, which embeds a spread ( $x_t^{cip}$ ) that reflects banks’ balance sheet costs.

We assume the only players who can engage in the riskless CIP arbitrage are a set of balance-sheet constrained banks. Specifically, we assume these banks choose the value of their positions in the CIP arbitrage trade,  $d_{B,t}^{cip}$ , to solve:

$$\max_{d_{B,t}^{cip}} \{x_t^{cip} d_{B,t}^{cip} - (\kappa/2) (d_{B,t}^{cip})^2\}, \quad (43)$$

where  $\kappa \geq 0$ . Here  $(\kappa/2) (d_{B,t}^{cip})^2$  captures non-risk-based balance sheet costs faced by banks. These costs arise because equity capital is costly and banks are subject to non-risk-based equity capital requirements (i.e., simple leverage ratios). Thus, banks take a position in the CIP arbitrage trade equal to:

$$d_{B,t}^{cip} = \kappa^{-1} x_t^{cip}. \quad (44)$$

These assumptions are purposely stark and serve to highlight the key mechanisms. In particular, our results would be qualitatively unchanged if some bond investors could engage in the

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<sup>28</sup>That is, the risk tolerance of foreign bond investors is  $\tau/Q_t$  in foreign currency terms.



CIP arbitrage trade in limited size. Similarly, we are assuming that banks have zero risk-bearing capacity, so that anytime they transact in the forward market, it is as part of a CIP arbitrage trade. However, we would obtain qualitatively similar results if we assumed that banks had finite risk-bearing capacity and thus could also take on risky FX positions.

**Market equilibrium** We need to clear four markets at time  $t$ : (i) the market for risky long-term domestic bonds; (ii) the market for risky long-term foreign bonds; (iii) the market for risky forward FX exposure, which we assume is in net supply  $s_t^q$ ; and (iv) the market for the CIP arbitrage trade.<sup>29</sup> Because forwards and the CIP arbitrage trade span the spot market, (iii) and (iv) are equivalent to clearing the forward and spot FX markets. This is because making a risky spot FX investment, which earns  $rx_{t+1}^q$ , is equivalent to combining a risky forward FX investment, which earns  $rx_{t+1}^q + x_t^{cip}$ , with a reverse CIP arbitrage trade, which earns  $-x_t^{cip}$ .

To clear the market for risky forward FX exposure at time  $t$ , investors must be willing to make a forward FX investment with a domestic notional value of  $s_t^q$ . Turning to the CIP arbitrage market, recall that the CIP arbitrage trade exchanges currency at the time  $t$  spot rate and to then reverses that exchange at  $t+1$  at the forward FX rate  $f_t^Q$ . For simplicity, we assume that the CIP arbitrage trade is in zero net supply ( $s_t^{cip} \equiv 0$ ), implying that banks must take the opposite side of bond investors' trades.<sup>30</sup>

**Proposition 6 Allowing for CIP deviations.** *Consider the extended model where the banks are potentially balance-sheet constrained. We have the following results:*

- *In the limiting case where banks are not balance-sheet constrained—i.e., where  $\kappa \rightarrow 0$ , CIP holds ( $x_t^{cip} \rightarrow 0$ ) and the extended model converges to the baseline model in Section 3.*
- *If banks are balance-sheet constrained ( $\kappa > 0$ ), we have*

$$E_t [rx_{t+1}^y] = \tau^{-1} [V_y \times s_t^y + C_{y,y*} \times s_t^{y*} + C_{y,q} \times s_t^q] - x_t^{cip}/2, \quad (45a)$$

$$E_t [rx_{t+1}^{y*}] = \tau^{-1} [C_{y,y*} \times s_t^y + V_y \times s_t^{y*} - C_{y,q} \times s_t^q] + x_t^{cip}/2, \quad (45b)$$

$$E_t [rx_{t+1}^q] = \tau^{-1} [C_{y,q} \times (s_t^y - s_t^{y*}) + V_q \times s_t^q] - x_t^{cip}, \quad (45c)$$

$$x_t^{cip} = -\kappa \underbrace{\frac{V_y + C_{y,y*}}{2(V_y + C_{y,y*}) + \tau\kappa}}_{<0} \times (s_t^y - s_t^{y*}). \quad (45d)$$

*Eqs. (45c) and (45d) show that the bond supply shocks  $s_t^y$  and  $s_t^{y*}$  push  $E_t[rx_{t+1}^q]$  and  $x_t^{cip}$  in opposite directions; as a result, these shocks push  $q_t$  and  $x_t^{cip}$  in the same direction.*

<sup>29</sup>To clearly separate the amount of risky FX exposure and the amount of balance-sheet intensive riskless funding that bond investors and banks must intermediate, we assume here that  $s_t^q$  is the net supply of risky FX exposure on a *forward* basis. Since bond investors can accommodate shocks to the supply of forward FX exposure without using scarce bank balance sheet capacity,  $s_t^q$  does not impact  $x_t^{cip}$ . By contrast, if  $s_t^q$  were instead the supply of risky FX exposure on a *spot* basis, then a rise in  $s_t^q$  would be associated with a decline in  $x_t^{cip}$ .

<sup>30</sup>In the Online Appendix, we add exogenous shocks to the supply of the CIP arbitrage trade that banks must undertake.

In the limiting case where banks balance-sheet costs vanish ( $\kappa \rightarrow 0$ ), CIP holds—i.e., we have  $x_t^{cip} \rightarrow 0$ , and equilibrium bond yields and exchange rates behave exactly as they did in the baseline model in Section 3. This limit arguably approximates the pre-2008 era, when CIP held and banks did not face binding non-risk-based equity capital constraints.

Next, consider the case where bank balance sheet costs are positive ( $\kappa > 0$ ). In this case, risk premia are given by Eq. (45) and the cross-currency basis  $x_t^{cip}$  is given by Eq. (45d). To understand the intuition for Eq. (45d), suppose there is an increase in the supply of long-term domestic bonds,  $s_t^y$ . As in our baseline model, this supply shock raises the domestic term premium and the FX premium, leading domestic currency to appreciate against foreign. Foreign bond investors then want to buy long-term domestic bonds, but they want to hedge the associated FX risk to isolate the elevated domestic term premium. Hedging the FX risk involves forward selling domestic currency. Because banks are balance-sheet constrained, banks are only willing to accommodate investor demand for FX hedges if domestic currency is weaker than CIP would imply in the forward market, meaning that the forward exchange rate  $f_t^q$  rises and the basis  $x_t^{cip}$  declines. Equivalently, the domestic bond supply shock boosts foreign bond investors' demand for short-term synthetic funding in domestic currency. Since banks are balance-sheet constrained, this shift in funding demand pushes up the synthetic domestic short rate ( $i_t^* + f_t^q - q_t$ ) relative to its cash counterpart ( $i_t$ ), thereby driving down the basis.

Eqs. (45d) and (45c) show that the two bond supply shocks ( $s_t^y, s_t^{y*}$ ) push  $x_t^{cip}$  and  $E_t [rx_{t+1}^q]$  in opposite directions. As a result, these supply shocks induce a positive correlation between the basis  $x_t^{cip}$  and the spot exchange rate  $q_t$ , consistent with the recent findings of Avdjiev, Du, Koch, and Shin (2019) and Jiang, Krishnamurthy, and Lustig (2019). Intuitively, in our model, demand to buy domestic currency in the spot market, which drives down  $q_t$ , is linked with hedging demand to sell domestic currency in the forward market, which drives down  $x_t^{cip}$ . Since risk premia are not directly observable but CIP deviations are, the CIP basis is an informative signal about the underlying supply-and-demand shocks that drive UIP failures in our model (i.e., movements in  $E_t [rx_{t+1}^q]$ ).<sup>31</sup>

Figure 2 illustrates these results. We show the impact of a shock to domestic bond supply on equilibrium expected returns as a function of bank capital cost,  $\kappa$ . As in the baseline model in Section 3, when  $\kappa = 0$ , we have  $x_t^{cip} = 0$ . Following an increase in domestic bond supply, foreign investors use FX forwards to hedge purchases their of domestic bonds. Banks costlessly supply these FX forwards when  $\kappa = 0$ . As we increase  $\kappa$ ,  $x_t^{cip}$  must decline to induce balance-sheet constrained banks to accommodate hedging demand from foreign investors.

CIP deviations generate an *endogenous* comparative advantage for domestic investors in domestic bonds because they can hold these bonds without bearing currency risk or paying the costs of hedging currency risk with FX forwards. This endogenous comparative advantage means that increasing balance sheet costs,  $\kappa$ , raises the impact of a domestic bond supply shock on domestic term premia ( $E_t [rx_{t+1}^y]$ ) and FX premia ( $E_t [rx_{t+1}^q]$ ), and reduces the impact on foreign term premia ( $E_t [rx_{t+1}^{y*}]$ ). Intuitively, foreign investors do less to accommodate the shock, raising the

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<sup>31</sup>Relatedly, Du, Hebert, and Huber (2019) argue that the CIP basis is a measure of how tightly banks' regulatory constraints are binding and therefore should price the typical portfolio returns studied in the intermediary-based asset pricing literature. They provide empirical evidence consistent with this argument.

impact on domestic term premia and lowering the impact on foreign term premia.

## 5 Model extensions

### 5.1 Further segmenting the global bond market

In this section, we further enrich the structure of intermediation in our model to capture two significant, real-world features of global bond and FX markets. First, real-world markets feature a variety of different investor types—each facing a different set of constraints—opening the door for meaningful segmentation *within* global bond and FX markets. Second, real-world bond and FX markets involve substantial trading flows between different investor types (Evans and Lyons [2002] and Froot and Ramadorai [2005]).

We first further segment the global bond market as in Gromb and Vayanos (2002), assuming some bond investors cannot trade short- and long-term bonds in both currencies. A first take-away is that, with further segmentation, exogenous bond supply shocks give rise to endogenous foreign exchange trading flows that are associated with changes in exchange rates. A second take-away is that a small amount of additional segmentation always increases the impact of bond supply shocks on exchange rates.

Our extended model features four types of bond investors. All types have mean-variance preferences over one-period-ahead wealth and a risk tolerance of  $\tau$  in domestic currency terms. Types only differ in their ability to trade different assets. Specifically:

1. *Domestic bond specialists*, present in mass  $\mu\pi$ , can only choose between short- and long-term domestic bonds—i.e., they can only engage in the domestic yield curve trade.
2. *Foreign bond specialists*, also present in mass  $\mu\pi$ , can only choose between short- and long-term foreign bonds—i.e., they can only engage in the foreign yield curve trade.
3. *FX specialists*, present in mass  $\mu(1 - 2\pi)$ , can only choose between short-term domestic and foreign bonds—i.e., they can only engage in the FX trade.
4. *Global bond investors*, present in mass  $(1 - \mu)$ , can hold short- and long-term bonds in both currencies and can engage in all three long-short trades.

We assume  $\mu \in [0, 1]$  and  $\pi \in (0, 1/2)$ . Increasing the combined mass of specialist types,  $\mu$ , is equivalent to introducing greater segmentation in the global bond market. Thus, our baseline model corresponds to the limiting case where  $\mu = 0$ . At the other extreme, markets are fully segmented when  $\mu = 1$ . And, when  $\mu \in (0, 1)$  markets are partially segmented.

Our domestic bond specialists are reminiscent of the specialized bond investors in Vayanos and Vila (2019) in the sense that their positions in long-term domestic bonds are a sufficient statistic for the expected returns on the domestic yield curve trade. Our FX specialists are similar to the FX intermediaries in Gabaix and Maggiori (2015): their FX positions are a sufficient statistic for the expected returns on the FX trade. In practice, we associate the domestic and foreign bond

specialists with market participants who, for institutional reasons, exhibit significant home-bias and are essentially unwilling to substitute between bonds in different currencies.

In the Online Appendix, we derive the following results:

**Proposition 7 *Further segmenting the bond market.*** *Suppose  $\rho \in (0, 1)$  and that fraction  $\mu$  of investors are specialists. We have the following results:*

- (i.) **Price impact.** *Suppose  $\sigma_{sy}^2 = \sigma_{sq}^2 = 0$ . (a) Greater segmentation increases own-market price impact.* Formally, for any  $a \in \{y, y^*, q\}$ ,  $\partial^2 E_t[rx_{t+1}^a]/\partial s_t^a \partial \mu > 0$ . (b) **Segmentation has a hump-shaped effect on cross-market price impact.** For any  $a_1 \in \{y, y^*, q\}$  and  $a_2 \neq a_1$ ,  $|\partial E_t[rx_{t+1}^{a_1}]/\partial s_t^{a_2}|$  is hump-shaped function of  $\mu$  with  $|\partial E_t[rx_{t+1}^{a_1}]/\partial s_t^{a_2}| > 0$  when  $\mu = 0$  and  $\partial E_t[rx_{t+1}^{a_1}]/\partial s_t^{a_2} = 0$  when  $\mu = 1$ . (c) **Greater segmentation increases bond market-wide price impact.** For any supply  $\mathbf{s}_t \neq \mathbf{0}$ , the expected return on the global bond market portfolio  $rx_{t+1}^{st} = \mathbf{s}_t' \mathbf{r}_{t+1}$  is increasing in  $\mu$ :  $\partial E_t[rx_{t+1}^{st}]/\partial \mu > 0$ .
- (ii.) **Segmentation leads to endogenous trading flows.** *Suppose  $\sigma_{sy}^2 \geq 0$ ,  $\sigma_{sq}^2 \geq 0$ . For any  $\mu \in (0, 1)$ , a shock to the supply of any asset  $a \in \{y, y^*, q\}$  triggers trading in all assets  $a' \neq a$  between global bond investors and specialist investors.*

Further segmenting the global bond market—i.e., increasing  $\mu$ —has two direct effects. First, as we increase  $\mu$ , there is an “inefficient risk-sharing” effect because fewer investors can absorb a given supply shock. This effect tends to increase the price impact of all supply shocks. Second, as we increase  $\mu$ , there is a “width of the pipe” effect because we increase the mass of specialist investors who do not alter their demand for their asset in response to shocks in other markets. This effect tends to diminish the impact of a supply shock in one market on prices in other markets because price impact is only transmitted across markets by global bond investors—“the pipe”—whose demands for each asset are impacted by shocks to other markets. Finally, there is an “endogenous risk” effect. To the extent that greater segmentation directly alters the price impact of supply shocks, greater segmentation affects equilibrium return volatility, further altering equilibrium price impact.

Part (i) of Proposition 7 characterizes equilibrium price impact as a function of  $\mu$  in the limit where supply risk vanishes ( $\sigma_{sy}^2 = \sigma_{sq}^2 = 0$ ).<sup>32</sup> In this limiting case, the endogenous risk effect disappears, leaving only the inefficient risk-sharing and width of the pipe effects. As we raise  $\mu$ , these two effects always increase the impact of a supply shock in market  $a$  on expected returns in that market:  $\partial^2 E_t[rx_{t+1}^a]/\partial s_t^a \partial \mu > 0$  for any  $a \in \{y, y^*, q\}$ . Cross-market price impact under partial segmentation is more complicated. For instance, consider how the FX risk premium responds to domestic bond supply,  $\partial E_t[rx_{t+1}^q]/\partial s_t^y$ , as a function of  $\mu$ . When there are only global bond investors ( $\mu = 0$ ), a shock to domestic bond supply raises expected returns on the FX trade:  $\partial E_t[rx_{t+1}^q]/\partial s_t^y > 0$ . This is the key result from our baseline model. By contrast, when markets

<sup>32</sup>To prove part (i) of the proposition and draw all figures in the paper, we assume there is some FX-specific fundamental risk. That is, we assume  $\lim_{T \rightarrow \infty} E_t[q_{t+T}] = q_t^\infty$  follows a random walk  $q_{t+1}^\infty = q_t^\infty + \varepsilon_{q^\infty, t+1}$  with  $\text{Var}_t[\varepsilon_{q^\infty, t+1}] = \sigma_{q^\infty}^2 > 0$ , implying  $q_t = q_t^\infty + \sum_{j=0}^{\infty} E_t[(i_{t+j}^* - i_{t+j}) - rx_{t+j+1}^q]$ . If  $\sigma_{q^\infty}^2 = 0$ , then in the absence of supply risk, FX is a redundant asset. FX returns are a linear combination of those on domestic and foreign bonds. Cross-market impact would still be hump-shaped in this case so long as  $\sigma_{sq}^2, \sigma_{sy}^2 > 0$ .

are completely segmented and there are no global bond investors, bond supply shocks have no impact on FX—i.e.,  $\partial E_t[rx_{t+1}^q]/\partial s_t^y = 0$  when  $\mu = 1$ . In between, however,  $\mu$  has a hump-shaped effect on cross-market price impact. This hump-shape reflects the combination of the inefficient risk-sharing effect, which typically leads  $\partial E_t[rx_{t+1}^q]/\partial s_t^y$  to rise with  $\mu$  and dominates when  $\mu$  is near 0, and the width of the pipe effect, which typically leads  $\partial E_t[rx_{t+1}^q]/\partial s_t^y$  to fall with  $\mu$  and dominates when  $\mu$  is near 1.

When we introduce stochastic supply shocks ( $\sigma_{s_y}^2 > 0$  and  $\sigma_{s_q}^2 > 0$ ), the endogenous risk effect comes into play. By continuity of the stable equilibrium in the model’s underlying parameters, the results in part (i) of Proposition 7 must continue to hold when supply risk is small. More generally, the endogenous risk effect typically amplifies the sum of the inefficient risk-sharing and width of pipe effects, so the hump-shaped profile of  $|\partial E_t[rx_{t+1}^q]/\partial s_t^y|$  becomes more pronounced in the presence of supply risk. In addition, when asset supply is stochastic, greater segmentation typically increases equilibrium market volatility. Furthermore, the endogenous risk effect typically steepens the relationship between segmentation  $\mu$  and the expected return on the global bond market portfolio.<sup>33</sup>

The results in Proposition 7 are illustrated in Figure 3. Panel A of Figure 3 plots the impact of a domestic bond supply shock on expected returns as a function of  $\mu$ . The plot shows that, while  $\partial E_t[rx_{t+1}^y]/\partial s_t^y$  is always increasing in  $\mu$ , segmentation has a hump-shaped effect on  $\partial E_t[rx_{t+1}^q]/\partial s_t^y$ . Unless  $\mu$  is near 1 and the global bond markets is highly segmented, the effect of bond supply shocks on foreign exchange exceeds that in our baseline model where  $\mu = 0$ . Thus, it is natural to conjecture that the impact of bond supply shocks on foreign exchange markets has risen in recent decades because  $\mu$  has fallen over time. In other words, relative to earlier periods where markets were highly segmented ( $\mu \approx 1$ ), the global bond market has become more integrated, raising  $\partial E_t[rx_{t+1}^q]/\partial s_t^y$  (Mylonidis and Kollias [2010], Pozzi and Wolswijk [2012]).

The next two plots in Panel B of Figure 3 show the trading response to a unit domestic bond supply shock as a function of  $\mu$ . When  $\mu \in (0, 1)$ , markets are partially segmented, global bond investors and the three specialist types disagree on the appropriate compensation for bearing factor risk exposure. Thus, as shown in part (ii) of Proposition 7, following a supply shock to any one asset, global bond investors trade across markets to align—but not equalize—the way that factor risk is priced in different markets. For instance, a shock to the supply of domestic bonds leads to foreign exchange trading between global bond investors and FX specialists. Specifically, following a positive shock to domestic bond supply, global bond investors want to increase their exposure to domestic bonds and reduce their exposure to the FX trade. FX specialists must take the other side, increasing their exposure to the FX trade. These endogenous FX trading flows are associated with an increase in FX risk premia and a depreciation of foreign currency. In this way, our extension with additional bond market segmentation endogenizes the kinds of capital market driven FX flows considered in Gabaix and Maggiori (2015). Rather than being exogenous quantities that specialist FX investors are required to absorb, these endogenous FX

<sup>33</sup>Formally, for any bond portfolio  $\mathbf{p}_t \neq \mathbf{0}$  with returns  $rx_{t+1}^{\mathbf{p}_t} = \mathbf{p}_t' \mathbf{r}\mathbf{x}_{t+1}$ , we typically have  $\partial \text{Var}_t[rx_{t+1}^{\mathbf{p}_t}]/\partial \mu > 0$ . When the endogenous risk effect is positive in this portfolio sense, then for any set of supply shocks  $\mathbf{s}_t \neq \mathbf{0}$ , the expected return on the global bond market portfolio  $rx_{t+1}^{\mathbf{s}_t} = \mathbf{s}_t' \mathbf{r}\mathbf{x}_{t+1}$  rises more steeply with  $\mu$ —i.e., the endogenous risk effect raises  $\partial E_t[rx_{t+1}^{\mathbf{s}_t}]/\partial \mu > 0$ .

flows are tied to supply-and-demand shocks for long-term bonds.

## 5.2 Adding unhedged bond investors

A variety of frictions, including constraints on short-selling or using derivatives, may limit some investors' ability to hedge FX risk. In our second extension, we add bond investors who cannot hedge FX risk—i.e., investors who cannot separately manage the FX exposure resulting from investments they make in non-local, long-term bonds. For example, if unhedged domestic investors want to buy long-term foreign bonds to capture the foreign term premium, they must take on exposure to foreign currency. Thus, unlike global bond investors, who can separately manage their exposures to foreign currency and the foreign yield-curve trade, these unhedged domestic investors always “staple together” the returns on the FX trade and the foreign yield-curve trade. We show that adding unhedged investors is like introducing a particular form of market segmentation. Thus, adding unhedged investors amplifies the effect of supply shocks on exchange rates and leads to endogenous trading flows.

Concretely, we assume there are three investor types—all with mean-variance preferences over one-period-ahead wealth and risk tolerance  $\tau$  in domestic currency terms—who only differ in terms of the assets they can trade:

1. *Unhedged domestic investors* are present in mass  $\eta/2$ . They can trade short-term domestic bonds, long-term domestic bonds, and long-term foreign bonds, but not short-term foreign bonds. Thus, if they buy long-term foreign bonds, they must take on foreign exchange exposure, generating an excess return of  $rx_{t+1}^{y^*} + rx_{t+1}^q$  over short-term domestic bonds.
2. *Unhedged foreign investors* are present in mass  $\eta/2$  and are the mirror image of unhedged domestic investors. If they buy long-term domestic bonds, they must take on FX exposure, generating an excess return of  $rx_{t+1}^y - rx_{t+1}^q$  over short-term foreign bonds.
3. *Global bond investors*, present in mass  $(1 - \eta)$ , can hold short- and long-term bonds in both currencies and can engage in all three carry trades.

Unhedged investors will exhibit home bias in equilibrium. For instance, since an FX-unhedged position in long-term domestic bonds is always riskier than the FX-hedged position, it is particularly risky for foreign unhedged investors to invest in domestic bonds. Thus, relative to global bond investors and domestic unhedged investors, foreign unhedged investors face a comparative disadvantage in holding long-term domestic bonds.

In the Online Appendix, we solve for equilibrium and obtain the following results:

**Proposition 8** *Adding unhedged bond investors.* Suppose  $\rho \in (0, 1)$  and that fraction  $\eta$  of bond investors cannot hedge FX risk. We have the following results:

- (i.) **Price impact.** Suppose  $\sigma_{sy}^2 = \sigma_{sa}^2 = 0$ . Increasing the fraction of unhedged investors  $\eta$ :
- (a) increases own-market price impact:  $\partial^2 E_t [rx_{t+1}^a] / \partial s_t^a \partial \eta > 0$  for all  $a \in \{y, y^*, q\}$ ; (b)

reduces the impact of domestic bond supply shocks on long-term foreign yields and vice-versa:  $\partial^2 E_t [rx_{t+1}^{y^*}] / \partial s_t^y \partial \eta < 0$  and  $\partial^2 E_t [rx_{t+1}^y] / \partial s_t^{y^*} \partial \eta < 0$ ; (c) increases the impact of bond supply shocks on exchange rates:  $\partial^2 E_t [rx_{t+1}^q] / \partial s_t^y \partial \eta > 0$  and  $\partial^2 E_t [rx_{t+1}^q] / \partial s_t^{y^*} \partial \eta < 0$ ; and (d) raises the expected returns on the bond market portfolio  $rx_{t+1}^{s_t} = \mathbf{s}'_t \mathbf{r}x_{t+1}$ :  $\partial E_t [rx_{t+1}^{s_t}] / \partial \eta > 0$  for any  $\mathbf{s}_t \neq \mathbf{0}$ .

(ii.) **Introducing unhedged bond investors leads to endogenous trading.** Suppose  $\sigma_{sy}^2 \geq 0$ , and  $\sigma_{sq}^2 \geq 0$ . For any  $\eta \in (0, 1]$ , a shock to the supply of any asset  $a \in \{y, y^*, q\}$  triggers trading in all assets  $a' \neq a$ .

Figure 3 shows how a domestic bond supply shock impacts expected returns of as a function of the fraction of unhedged investors  $\eta$ . In our baseline model where  $\eta = 0$ , an increase in domestic bond supply  $s_t^y$  raises the expected returns on all three trades. As  $\eta$  rises, the impact on domestic bond returns rises. Own-market price impact rises because we are replacing global bond investors with unhedged foreign investors who are at a comparative disadvantage at absorbing this domestic bond supply shock. Thus,  $\partial E_t [rx_{t+1}^y] / \partial s_t^y$  must rise with  $\eta$  to induce unhedged domestic investors and the remaining global bond investors to pick up the slack. The same comparative advantage logic explains why the impact of a domestic supply shock on foreign bond returns declines with  $\eta$ : there are fewer players who are willing to elastically substitute between long-term domestic and foreign bonds. As a result,  $\partial E_t [rx_{t+1}^{y^*}] / \partial s_t^y$  must fall with  $\eta$ : otherwise unhedged foreign investors' demand for foreign bonds will exceed the (unchanged) net supply of foreign bonds. Finally, as  $\eta$  increases, the domestic bond supply shock has a larger impact on foreign exchange markets. To see the intuition, note that the foreign currency demands of all three investor types are increasing in  $E_t [rx_{t+1}^q]$  and  $E_t [rx_{t+1}^{y^*}]$  and decreasing in  $E_t [rx_{t+1}^y]$ . Thus, with  $\partial E_t [rx_{t+1}^y] / \partial s_t^y$  rising with  $\eta$  and  $\partial E_t [rx_{t+1}^{y^*}] / \partial s_t^y$  falling,  $\partial E_t [rx_{t+1}^q] / \partial s_t^y$  must rise with  $\eta$  to keep the foreign exchange market in equilibrium.

The three plots in Panel B of Figure 3 show the trading response to a positive shock to domestic bond supply as a function of  $\eta$ . In keeping with their comparative advantage, unhedged domestic investors and global bond investors absorb this shock to domestic bond supply. Unhedged domestic investors buy domestic bonds and—to lower their common short-rate exposure—reduce their unhedged holdings of foreign bonds. Global rates investors buy long-term domestic bonds and hedge their increased exposure to short-term domestic rates by reducing their holdings of long-term foreign bonds and foreign exchange. Thus, both unhedged domestic investors and global bond investors sell long-term foreign bonds and foreign currency. In equilibrium, unhedged foreign investors must take the opposite side of these flows, buying both long-term foreign bonds and foreign currency. And, in order to buy foreign currency, unhedged foreign investors must reduce their holdings of long-term domestic bonds.

This extension captures one common intuition about how QE policies may impact exchange rates rates. For instance, explaining in May 2015 how he believed large-scale bond purchases by the European Central Bank had weakened the euro, President Mario Draghi commented:

[The ECB's bond purchases] encourage investors to shift holdings into other asset classes ... and across jurisdictions, reflected in a falling of the exchange rate.

Specifically, domestic QE policies—i.e., a reduction in  $s_t^y$ —lead unhedged domestic investors to buy foreign bonds on an unhedged basis, putting additional downward pressure on domestic currency relative to our baseline model. In summary, the presence of unhedged investors gives rise to a form of segmentation in the global bond market. This segmentation implies that a reduction in domestic bond supply leads to trading flows in the FX market and a larger depreciation of domestic currency than in our baseline model.

### 5.3 Interest-rate insensitive assets

The key intuition in our baseline model is that foreign exchange is an “interest-rate sensitive” asset—i.e., it is highly exposed to news about future short-term interest rates. This leads shocks to the supply of other rate-sensitive assets—such as long-term domestic and foreign bonds—to impact exchange rates. However, in the absence of additional frictions, shocks to the supply of interest-rate *insensitive* assets—assets whose returns are not naturally exposed to short rate risk—will *not* impact exchange rates. For instance, we can add domestic and foreign stocks to the model and make a series of (admittedly strong) assumptions which guarantee that the excess returns on domestic and foreign equities are naturally uncorrelated with those on foreign exchange.<sup>34</sup>

If all equity investors can separately manage their FX exposures and CIP holds, then equity supply shocks will not impact equilibrium exchange rates. In this case, an increase in the supply of domestic equities pushes up the domestic equity risk premium, leaving FX premia unchanged. The shock will lead foreign equity investors to purchase domestic equities, but they will do so on a fully FX-hedged basis, leaving the FX exposure of equity investors and global bond investors unchanged.

However, if there are CIP violations as in Section 4 or if some equity investors cannot hedge FX risk as in Subsection 5.2, then equity supply shocks will also impact spot FX rates. Under these conditions, equity investors will not fully FX-hedge their non-local investments—either due to the endogenous cost of hedging in the former case or by assumption in the latter case. As a result, equity supply shocks will alter the FX exposures of non-local equity investors and, thus by market-clearing, global bond investors. In this way, shocks to the supply-and-demand for interest-rate-*insensitive* assets can impact spot exchange rates when FX hedging is limited, consistent with recent empirical findings (Hau and Rey [2005], Hau, Massa, and Peress [2009], Lilley, Maggiori, Neiman, and Schreger [2019], and Pandolfi and Williams [2019]). This line of reasoning suggests that the rise in bank balance sheet costs—and the corresponding CIP deviations—that have emerged since 2008 may have increased the set of capital market flows that can impact spot exchange rates. Furthermore, when bank balance sheet costs lead to CIP deviations, the cross-border flows triggered by shocks to interest-rate-insensitive assets can lead

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<sup>34</sup>Unexpected stock returns depend on news about future dividend growth, news about future short rates, and news about future equity risk premia. For the sake of the argument, we assume any bad news about higher short-term rates is perfectly offset by good news about future dividend growth. We also assume that news about future equity risk premia is driven by equity supply-and-demand shocks that are independent of those driving bond and FX markets.



spot exchange rates and the CIP basis to co-move positively as in Section 4.

## 6 Conclusion

We develop a workhorse model in which the limited risk-bearing capacity of global bond market investors plays a central role in determining foreign exchange rates. In our baseline model, specialized bond investors must accommodate supply-and-demand shocks in the markets for foreign and domestic long-term bonds as well as in the foreign exchange market.

This simple model captures many features of the data, including (i) correlations between realized excess returns on foreign currency and long-term bonds, (ii) the relationship between the foreign exchange risk premium and term premia, (iii) the effects of quantitative easing policies on exchange rates, and (iv) the fact that currency trades are more profitable when implemented using short-term bonds than using long-term bonds. In addition, our baseline model provides a unified account linking the Fama (1984) and Campbell-Shiller (1991) predictability results. We then enrich the structure of intermediation in our model in two ways. First, we add balance-sheet constrained banks, which allow us to study CIP deviations. Second, we further segment the bond market, introducing investors who cannot flexibly trade bonds of any maturity in both currencies. This segmentation leads to endogenous trading flows in currency markets that are associated with movements in the exchange rate. Overall, our paper shows that the structure of financial intermediation in bond and currency markets helps explain a number of empirical regularities in these markets.

From a policy perspective, our model demonstrates that the ability to influence exchange rates—and hence presumably trade flows—remains a potentially important channel for monetary policy transmission even when central banks are pinned against the zero lower bound (ZLB) and must rely on quantitative easing to provide monetary accommodation. Indeed, our analysis leaves open the interesting possibility that when other conventional channels of transmission are compromised by low rates (Brunnermeier and Koby [2019]), this QE-exchange-rate channel may become a *relatively more important* part of the overall monetary transmission mechanism. If so, and given the zero-sum nature of this channel across countries, arguments for monetary-policy coordination e.g., (Rajan [2016]) may gather more force near the ZLB. To be clear, neither our model nor any of the evidence that we have presented gives decisive guidance on this point. But the model does provide a framework in which questions of this sort can be pursued more rigorously.

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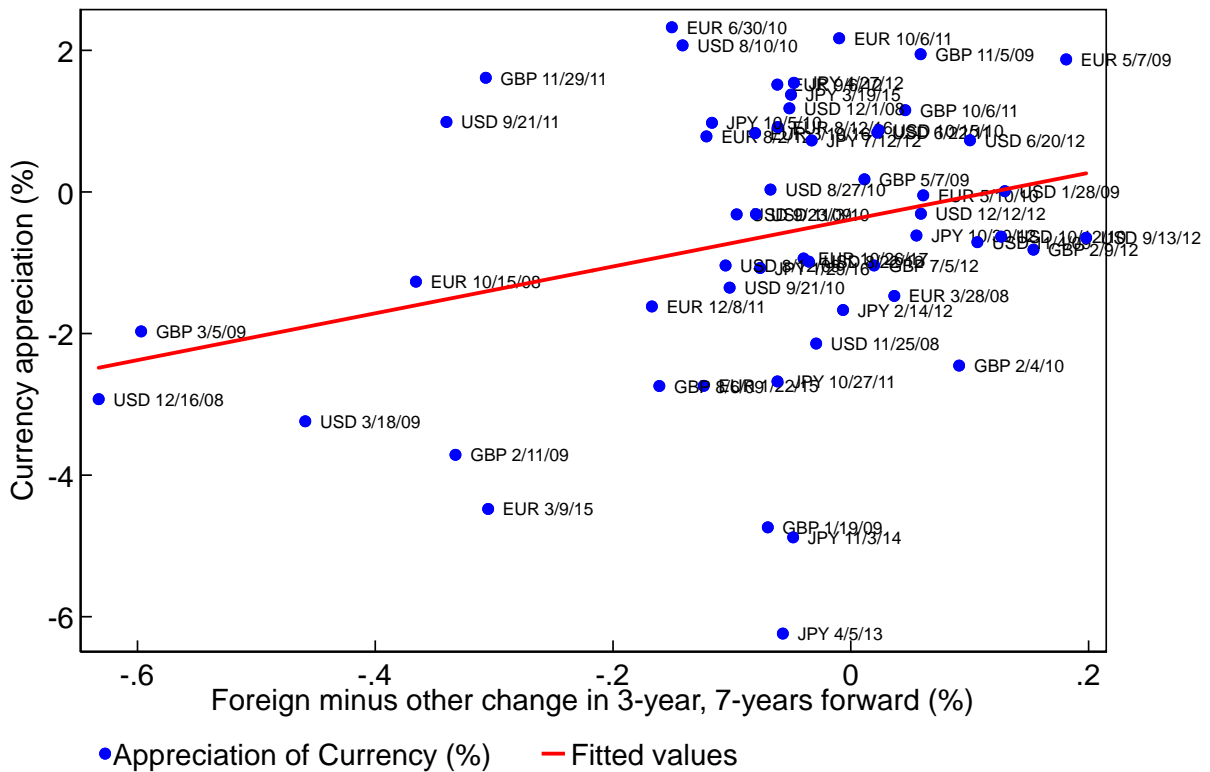
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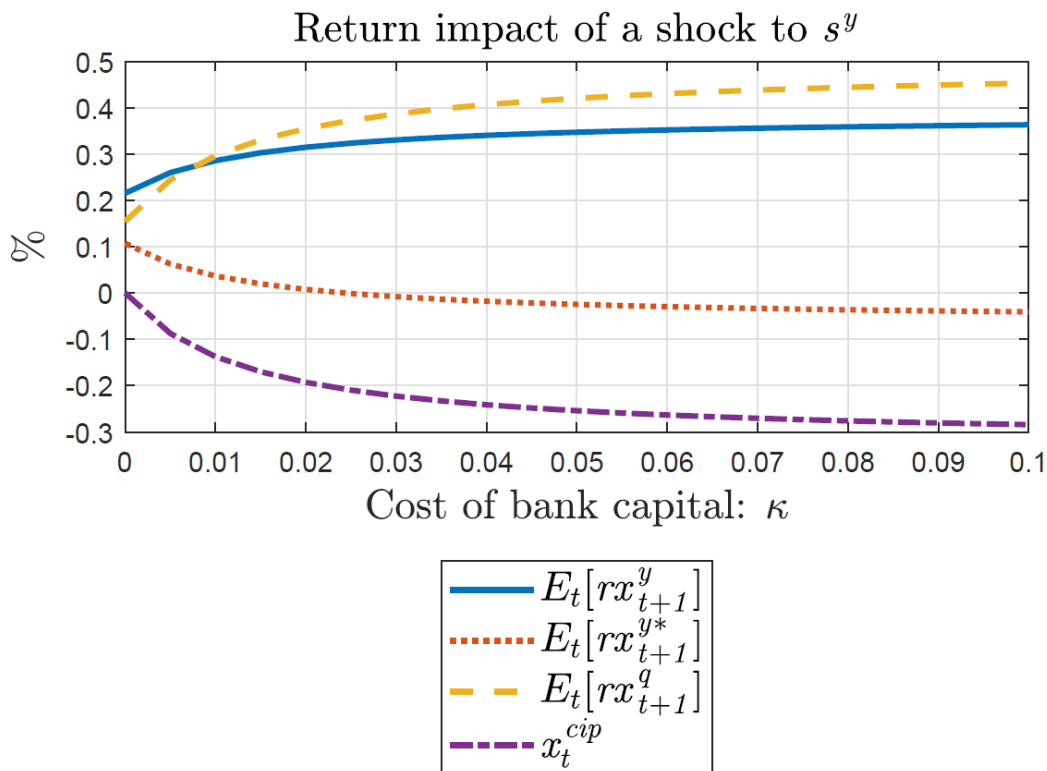
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**Figure 1. Movements in foreign exchange versus differential movements in forward rates on QE announcement dates.** The figure shows the movement in foreign exchange rates versus movements in the difference between foreign and domestic long-term forward rates around Quantitative Easing (QE) announcement dates by the U.S. Federal Reserve, the European Central Bank, the Bank of England, and the Bank of Japan. For an announcement on date  $t$ , we show the change in the foreign exchange rate and the movement in foreign minus domestic long-term rates from day  $t - 2$  to day  $t + 2$ . The long-term forward rate is the 3-year yield, 7-years forward. For the U.S. announcements, we show the average appreciation of the dollar relative to euro, pound, and yen versus the movement in U.S. long-term forward rates minus the average movement in forward rates for the euro, pound, and yen. For the other three currencies, we show their appreciation relative to the dollar versus the movement in the local currency forward rate minus the dollar forward rate.

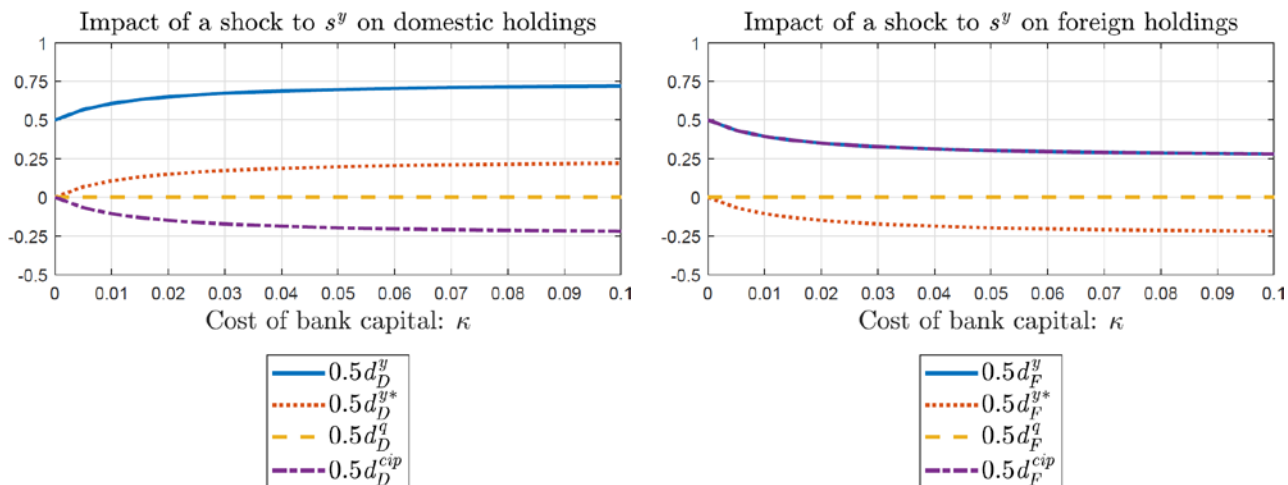


**Figure 2. Allowing for deviations from covered-interest-rate parity (CIP).** This figure illustrates the model allowing for CIP deviations from Section 4. The figure shows the impact of a shock to domestic bond supply on expected returns and investor holdings as a function of banks' costs of capital,  $\kappa$ . We chose the other model parameters so each period represents one month. We assume:  $\sigma_i = 0.3\%$ ,  $\phi_i = 0.98$ ,  $\rho = 0.5$ ,  $\sigma_{s^y} = 1$ ,  $\phi_{s^y} = 0.95$ ,  $\sigma_{s^q} = 1$ ,  $\phi_{s^q} = 0.95$ ,  $\sigma_{s^{cip}} = 1$ ,  $\phi_{s^{cip}} = 0.95$ ,  $\sigma_{q^\infty} = 0.5\%$ ,  $\delta = 119/120$  (i.e., the long-term bond has a duration of 120 months or 10 years), and,  $\tau = 1.75$ .

Panel A: Impact of a large shock (4 times  $\sigma_{s^y}$ ) to domestic bond supply ( $s^y$ ) on expected returns

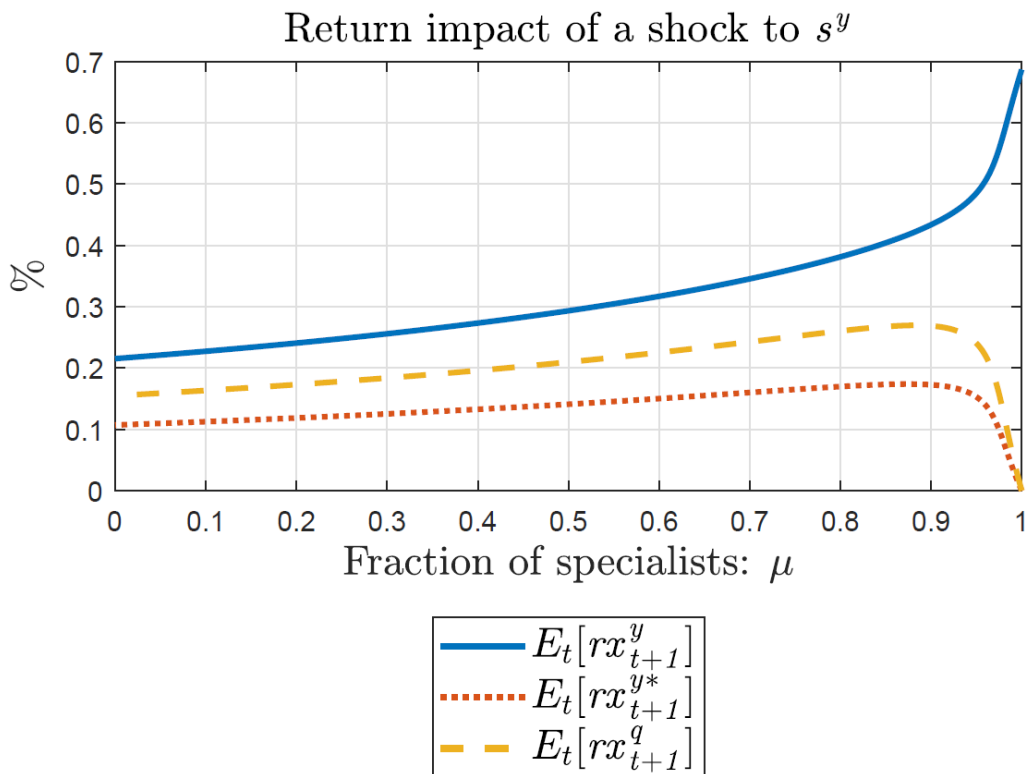


Panel B: Impact of a unit shock to domestic bond supply ( $s^y$ ) on investor holdings

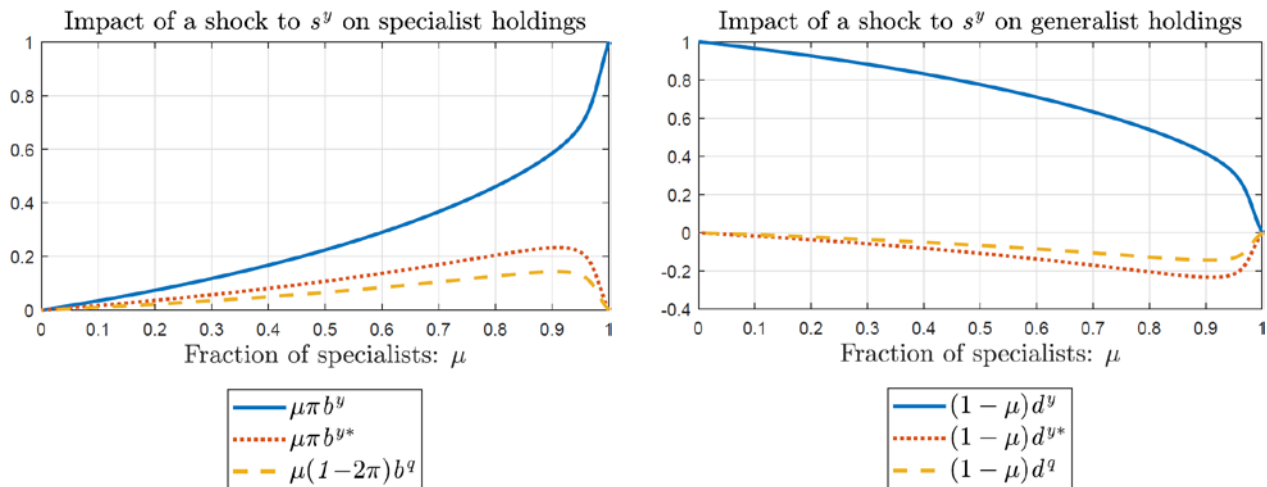


**Figure 3. Further segmenting the global bond markets.** This figure illustrates the model with further segmentation from Section 5.1. The figure shows the impact of a shock to domestic bond supply on expected returns and investor holdings as a function of the fraction of specialists,  $\mu$ . The figure assumes  $\pi = 1/3$ , so specialists are evenly split between domestic bonds, foreign bonds, and foreign exchange. We chose the other parameters so each period represents one month. We assume:  $\sigma_i = 0.3\%$ ,  $\phi_i = 0.98$ ,  $\rho = 0.5$ ,  $\sigma_{s^y} = 1$ ,  $\phi_{s^y} = 0.95$ ,  $\sigma_{s^q} = 1$ ,  $\phi_{s^q} = 0.95$ ,  $\sigma_{q^\infty} = 0.5\%$ ,  $\delta = 119/120$  (i.e., the long-term bond has a duration of 120 months or 10 years), and  $\tau = 1.75$ .

Panel A: Impact of a large shock (4 times  $\sigma_{s^y}$ ) to domestic bond supply ( $s^y$ ) on expected returns



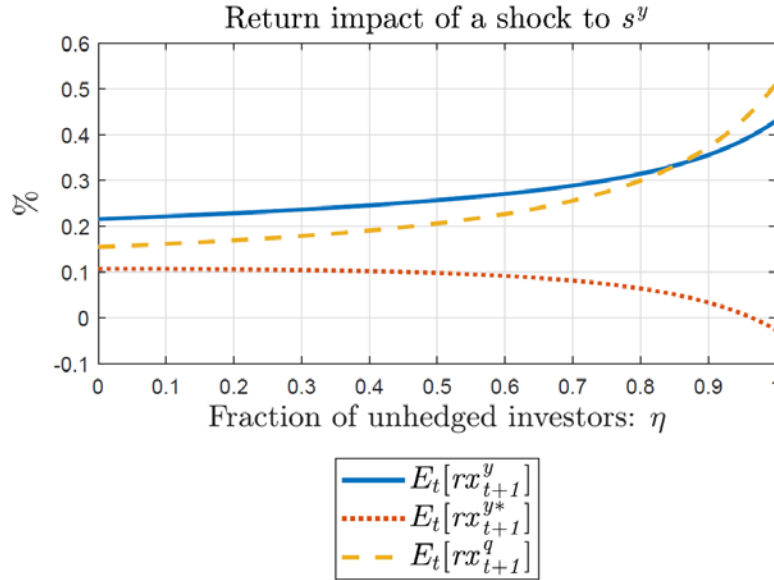
Panel B: Impact of a unit shock to domestic bond supply ( $s^y$ ) on investor holdings



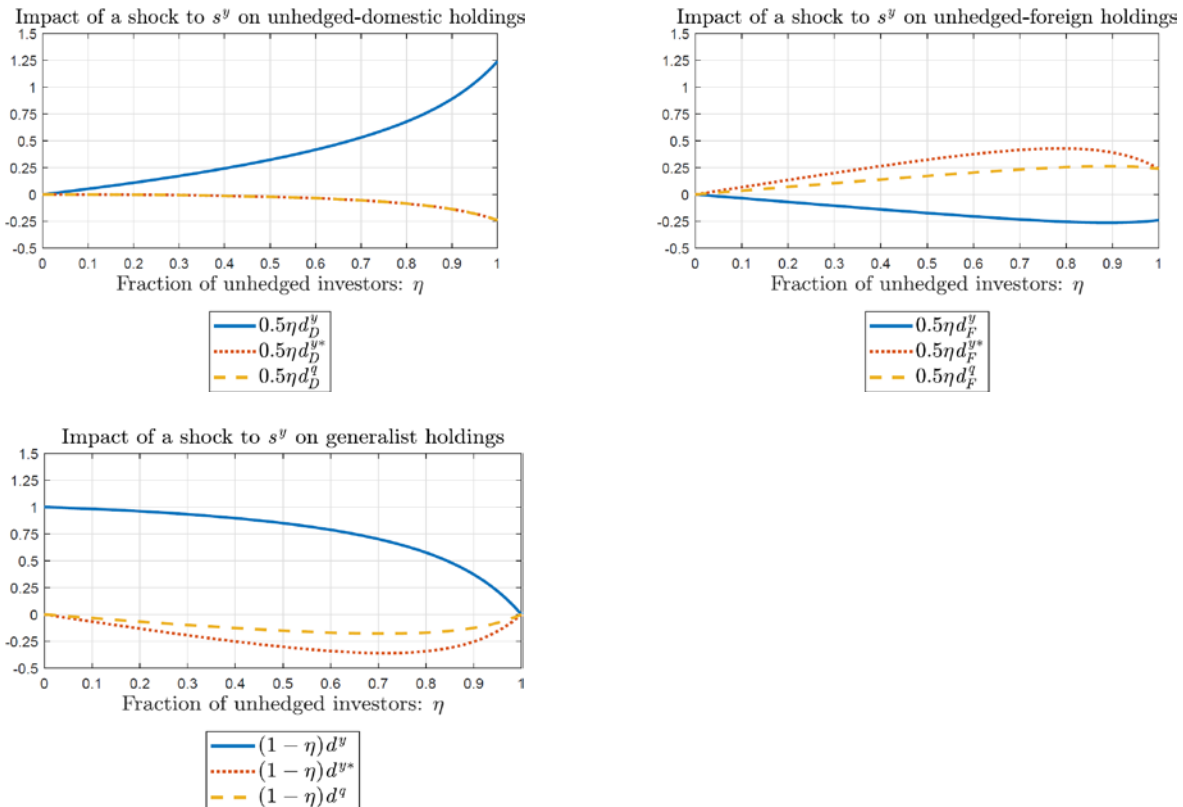


**Figure 4. Unhedged bond investors.** This figure illustrates the model with unhedged bond investors from Subsection 5.2. The figure shows the impact of a shock to domestic bond supply on expected returns and investor holdings as a function of the fraction of unhedged investors,  $\eta$ . We chose the other model parameters so each period represents one month. We assume:  $\sigma_i = 0.3\%$ ,  $\phi_i = 0.98$ ,  $\rho = 0.5$ ,  $\sigma_{s^y} = 1$ ,  $\phi_{s^y} = 0.95$ ,  $\sigma_{s^q} = 1$ ,  $\phi_{s^q} = 0.95$ ,  $\sigma_{q^\infty} = 0.5\%$ ,  $\delta = 119/120$  (i.e., the long-term bond has a duration of 120 months or 10 years), and  $\tau = 1.75$ .

Panel A: Impact of a large shock (4 times  $\sigma_{s^y}$ ) to domestic bond supply ( $s^y$ ) on expected returns



Panel B: Impact of a unit shock to domestic bond supply ( $s^y$ ) on investor holdings



**Table 1. Contemporaneous relationship between movements in foreign exchange, short-term interest rates, and long-term interest rates.** This table presents monthly panel regressions of the form:

$$\Delta_h q_{c,t} = A_c + B \times \Delta_h (i_{c,t}^* - i_t) + D \times \Delta_h (y_{c,t}^* - y_t) + \Delta_h \varepsilon_{c,t},$$

and

$$\Delta_h q_{c,t} = A_c + B_1 \times \Delta_h i_{c,t}^* + B_2 \times \Delta_h i_t + D_1 \times \Delta_h y_{c,t}^* + D_2 \times \Delta_h y_t + \Delta_h \varepsilon_{c,t}.$$

We regress  $h$ -month changes in the foreign exchange rate on  $h$ -month changes in short-term interest rates and in distant forward rates in both the foreign currency and in U.S. dollars. All regressions include currency fixed effects. We show results for Euro-USD, GBP-USD, and JPY-USD where a higher value of  $q_{c,t}$  means that currency  $c$  is stronger versus to the dollar. The sample runs from 2001m1 to 2017m12. Our proxy for the short-term interest rate in each currency is the 1-year government yield. Our proxy for the long-term interest rate is the 10-year government bond yield. For regressions involving  $h$ -month changes, we report Driscoll-Kraay (1998) standard errors—the panel data analog to Newey-West (1987) standard errors—allowing for serial correlation up to *ceiling*( $1.5 \times h$ ) lags. \*, \*\*, and \*\*\* indicate statistical significance at the 0.10, 0.05, and 0.01 levels, respectively. Statistical significance is computed using the asymptotic theory of Kiefer and Vogelsang (2005).

	$h = 3$ -month changes				$h = 12$ -month changes			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\Delta_h (i_{c,t}^* - i_t)$	4.68*** (1.63)	3.51** (1.69)			2.39 (1.54)	0.80 (1.64)		
$\Delta_h (y_{c,t}^* - y_t)$		4.37*** (1.20)				7.37*** (1.71)		
$\Delta_h i_{c,t}^*$			7.00*** (1.32)	5.86*** (1.34)			5.60*** (1.37)	2.45 (1.90)
$\Delta_h i_t$			-3.87*** (1.18)	-2.50** (1.13)			-1.84 (1.17)	-0.01 (1.27)
$\Delta_h y_{c,t}^*$				5.09*** (1.48)				11.51*** (2.26)
$\Delta_h y_t$				-4.83*** (1.07)				-7.44*** (1.91)
DK lags	5	5	5	5	18	18	18	18
$N$	612	612	612	612	612	612	612	612
R-squared	0.14	0.19	0.19	0.25	0.07	0.16	0.16	0.28

**Table 2. Contemporaneous relationship between movements in foreign exchange, short-term interest rates, and long-term forward rates.** This table presents monthly panel regressions of the form:

$$\Delta_h q_{c,t} = A_c + B \times \Delta_h (i_{c,t}^* - i_t) + D \times \Delta_h (f_{c,t}^* - f_t) + \Delta_h \varepsilon_{c,t},$$

and

$$\Delta_h q_{c,t} = A_c + B_1 \times \Delta_h i_{c,t}^* + B_2 \times \Delta_h i_t + D_1 \times \Delta_h f_{c,t}^* + D_2 \times \Delta_h f_t + \Delta_h \varepsilon_{c,t}.$$

We regress  $h$ -month changes in the foreign exchange rate on  $h$ -month changes in short-term interest rates and in distant forward rates in both the foreign currency and in U.S. dollars. All regressions include currency fixed effects. We show results for Euro-USD, GBP-USD, and JPY-USD where a higher value of  $q_{c,t}$  means that currency  $c$  is stronger versus to the dollar. The sample runs from 2001m1 to 2017m12. Our proxy for the short-term interest rate in each currency is the 1-year government bond yield. Our proxy for the distant forward rate is the 3-year, 7-year forward government bond yield. For regressions involving  $h$ -month changes, we report Driscoll-Kraay (1998) standard errors allowing for serial correlation up to *ceiling*( $1.5 \times h$ ) lags. \*, \*\*, and \*\*\* indicate statistical significance at the 0.10, 0.05, and 0.01 levels, respectively. Statistical significance is computed using the asymptotic theory of Kiefer and Vogelsang (2005).

	$h = 3$ -month changes				$h = 12$ -month changes			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\Delta_h (i_{c,t}^* - i_t)$	4.68*** (1.63)	4.72*** (1.56)			2.39 (1.54)	2.63 (1.51)		
$\Delta_h (f_{c,t}^* - f_t)$		2.99*** (0.85)				4.01*** (1.33)		
$\Delta_h i_{c,t}^*$			7.00*** (1.32)	7.02*** (1.21)			5.60*** (1.37)	5.33*** (1.37)
$\Delta_h i_t$			-3.87*** (1.18)	-3.89*** (1.11)			-1.84 (1.17)	-1.62 (1.16)
$\Delta_h f_{c,t}^*$				3.33*** (1.15)				7.10*** (1.45)
$\Delta_h f_t$				-3.04*** (0.76)				-3.77** (1.31)
DK lags	5	5	5	5	18	18	18	18
$N$	612	612	612	612	612	612	612	612
R-squared	0.14	0.18	0.19	0.23	0.07	0.12	0.16	0.24

**Table 3. Forecasting foreign minus domestic bond excess return using short-term interest rates and long-term forward rates.** This table presents monthly panel forecasting regressions of the form:

$$rx_{c,t \rightarrow t+h}^{y*} - rx_{c,t \rightarrow t+h}^y = A_c + B \times (i_{c,t}^* - i_t) + D \times (f_{c,t}^* - f_t) + \varepsilon_{c,t \rightarrow t+h},$$

and

$$rx_{c,t \rightarrow t+h}^{y*} - rx_{c,t \rightarrow t+h}^y = A_c + B_1 \times i_{c,t}^* + B_2 \times i_t + D_1 \times f_{c,t}^* + D_2 \times f_t + \varepsilon_{c,t \rightarrow t+h}.$$

We forecast the difference between foreign and domestic  $h$ -month bond returns using short-term interest rates and distant forward rates in both the foreign currency and in U.S. dollars. All regressions include currency fixed effects. We show results for Euro-USD, GBP-USD, and JPY-USD where a higher value of  $q_{c,t}$  means that currency  $c$  is stronger versus to the dollar. The sample runs from 2001m1 to 2017m12. Our proxy for the short-term interest rate in each currency is the 1-year government bond yield. Our proxy for the distant forward rate is the 3-year, 7-year forward government bond yield.  $rx_{c,t \rightarrow t+h}^{y*} - rx_{c,t \rightarrow t+h}^y$  is the difference between the  $h$ -month excess returns on 10-year foreign bonds and those on 10-year domestic bonds—i.e., the difference between the returns on two yield-curve carry trades that borrow short- and lend long-term. For regressions involving  $h$ -month excess returns, we report Driscoll-Kraay (1998) standard errors allowing for serial correlation up to *ceiling*( $1.5 \times h$ ) lags. \*, \*\*, and \*\*\* indicate statistical significance at the 0.10, 0.05, and 0.01 levels, respectively. Statistical significance is computed using the asymptotic theory of Kiefer and Vogelsang (2005).

	$h = 3$ -month excess returns				$h = 12$ -month excess returns			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$i_{c,t}^* - i_t$	-0.22 (0.14)	-0.28** (0.14)			-0.42 (0.41)	-0.53 (0.45)		
$f_{c,t}^* - f_t$		1.68*** (0.31)				4.16*** (0.45)		
$i_{c,t}^*$			-0.38** (0.15)	-0.18 (0.16)			-1.06** (0.42)	-0.58 (0.42)
$i_t$			0.08 (0.16)	0.16 (0.15)			-0.02 (0.44)	0.17 (0.44)
$f_{c,t}^*$				1.27*** (0.30)				3.02*** (0.44)
$f_t$				-1.65*** (0.33)				-3.90*** (0.46)
DK lags	5	5	5	5	18	18	18	18
$N$	609	609	609	609	582	582	582	582
R-squared	0.01	0.12	0.03	0.15	0.01	0.29	0.13	0.37

Table 4. Forecasting foreign exchange excess return using short-term interest rates and long-term forward rates. This table presents monthly panel forecasting regressions of the form:

$$rx_{c,t \rightarrow t+h}^q = A_c + B \times (i_{c,t}^* - i_t) + D \times (f_{c,t}^* - f_t) + \varepsilon_{c,t \rightarrow t+h},$$

and

$$rx_{c,t \rightarrow t+h}^q = A_c + B_1 \times i_{c,t}^* + B_2 \times i_t + D_1 \times f_{c,t}^* + D_2 \times f_t + \varepsilon_{c,t \rightarrow t+h}.$$

In words, we forecast  $h$ -month foreign exchange excess returns using short-term interest rates and distant forward rates in both the foreign currency and in U.S. dollars. All regressions include currency fixed effects. We show results for Euro-USD, GBP-USD, and JPY-USD where a higher value of  $q_{c,t}$  means that currency  $c$  is stronger versus to the dollar. The sample runs from 2001m1 to 2017m12. Our proxy for the short-term interest rate in each currency is the 1-year government bond yield. Our proxy for the distant forward rate is the 3-year, 7-year forward government bond yield.  $rx_{c,t \rightarrow t+h}^q$  is the  $h$ -month return on the FX carry trade strategy that borrows short-term in U.S. dollars and lends short-term in currency  $c$ . For regressions involving  $h$ -month excess returns, we report Driscoll-Kraay (1998) standard errors allowing for serial correlation up to *ceiling*( $1.5 \times h$ ) lags. \*, \*\*, and \*\*\* indicate statistical significance at the 0.10, 0.05, and 0.01 levels, respectively. Statistical significance is computed using the asymptotic theory of Kiefer and Vogelsang (2005).

	$h = 3$ -month excess returns				$h = 12$ -month excess returns			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$i_{c,t}^* - i_t$	-0.00 (0.36)	0.06 (0.34)			0.26 (1.47)	0.38 (1.43)		
$f_{c,t}^* - f_t$		-1.47*** (0.49)				-4.44*** (1.27)		
$i_{c,t}^*$			0.13 (0.43)	-0.24 (0.49)			1.05 (1.73)	0.11 (1.73)
$i_t$			0.11 (0.35)	0.07 (0.33)			0.28 (1.28)	0.14 (1.23)
$f_{c,t}^*$				-0.79 (0.57)				-2.32 (1.64)
$f_t$				1.52*** (0.52)				4.21*** (1.39)
DK lags	5	5	5	5	18	18	18	18
$N$	609	609	609	609	582	582	582	582
R-squared	0.00	0.03	0.01	0.05	0.00	0.07	0.04	0.11

**Table 5. Daily movements in foreign exchange, short-term interest rates, and long-term forward rates on QE announcement dates.** This table presents daily panel regressions of the form:

$$\Delta_4 q_{c,t+2} = A + B \times \Delta_4 (i_{c,t+2}^* - i_{t+2}) + D \times \Delta_4 (f_{c,t+2}^* - f_{t+2}) + \Delta_4 \varepsilon_{c,t+2},$$

and

$$\Delta_4 q_{c,t+2} = A + B_1 \times \Delta_4 i_{c,t+2}^* + B_2 \times \Delta_4 i_{t+2} + D_1 \times \Delta_4 f_{c,t+2}^* + D_2 \times \Delta_4 f_{t+2} + \Delta_4 \varepsilon_{c,t+2}.$$

on days with major QE news announcements. In words, we regress 4-day changes in the foreign exchange rate on 4-day changes in short-term interest rates and in distant forward rates in both the foreign currency and in U.S. dollars. For an announcement on date  $t$ , we look at changes from date  $t - 2$  to  $t + 2$ . We show results for Euro-USD, GBP-USD, and JPY-USD where a higher value of  $q_{c,t}$  means that currency  $c$  is stronger versus to the dollar. Our proxy for the short-term interest rate in each currency is the 1-year government bond yield. Our proxy for the distant forward rate is the 3-year, 7-year forward government bond yield. Standard errors are clustered by date in these specifications. \*, \*\*, and \*\*\* indicate statistical significance at the 10%, 5%, and 1% levels.

	(1)	(2)	(3)	(4)
$\Delta_4 (i_{c,t+2}^* - i_{t+2})$	7.92** (3.26)	10.46*** (1.90)		
$\Delta_4 (f_{c,t+2}^* - f_{t+2})$		4.62*** (1.12)		
$\Delta_4 i_{c,t+2}^*$			7.36** (3.22)	10.17*** (2.00)
$\Delta_4 i_{t+2}$			-15.66** (7.35)	-12.70** (5.89)
$\Delta_4 f_{c,t+2}^*$				4.53*** (1.35)
$\Delta_4 f_{t+2}$				-4.43*** (1.28)
$N$	95	95	95	95
R-squared	0.10	0.31	0.14	0.31

**Table 6: Comparison of our segmented-markets, quantity-driven model of foreign exchange (FX) with leading consumption-based models.**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	FX rates respond to supply and demand for assets in different currencies	Real short rates fall in recessions	Real short rates fall in “bad times” for bond investors	Real term premia can be positive: $E_t[rx_{t+1}^y] > 0$	Shocks to $i_{t+1}^* - i_{t+1}$ associated with foreign currency appreciation: $Cov_t[rx_{t+1}^q, i_{t+1}^* - i_{t+1}] > 0$	FX trade loses (makes) money when foreign (domestic) yield-curve trade does: $Cov_t[rx_{t+1}^q, rx_{t+1}^{y*} - rx_{t+1}^y] < 0$ .	$E_t[rx_{t+1}^q]$ negatively related to $E_t[rx_{t+1}^{y*} - rx_{t+1}^y]$	Fama ('84) FX carry trade: $E_t[rx_{t+1}^q]$ increasing in $(i_t^* - i_t)$	Campbell-Shiller ('91) yield curve carry trade: $E_t[rx_{t+1}^{y*}]$ is increasing in $(y_t - i_t)$	Real yield curve steep when short rates low: $(y_t - i_t)$ decreasing in $i_t$	Lustig et al ('19): Long-term FX carry trade less profitable than short-term trade
Data	Yes	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Our model	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Textbook C-CAPM model: Power utility, homoskedastic growth shocks, positive autocorrelation of growth <sup>i</sup>	No	Yes	Yes	No	No	No	N/A	N/A	N/A	Yes	N/A
Non-standard C-CAPM: Power utility, homoskedastic growth shocks, negative autocorrelation of growth <sup>ii</sup>	No	No	No	Yes	Yes	Yes	N/A	N/A	N/A	Yes	N/A
Long-run risks: News about long-run growth, stochastic volatility, EZ-W utility, CRRRA ( $\gamma$ ) exceeds inverse-EIS ( $\psi^{-1}$ ). <sup>iii</sup>	No	Yes	Yes	No	No	No	No	Yes	No/Yes	Yes/No	No
Long-run risks: News about long-run growth, stochastic volatility, EZ-W utility, inverse-EIS ( $\psi^{-1}$ ) exceeds CRRRA ( $\gamma$ ). <sup>iv</sup>	No	Yes	No	Yes	Yes	Yes	Yes	No	No/Yes	Yes/No	Yes
Time-varying probability of rare consumption disasters <sup>v</sup>	No	Yes	Yes	No	No	No	No	Yes	No/Yes	Yes/No	No
Habit formation: Short rate rises when surplus-consumption ratio rises <sup>vi</sup>	No	Yes	Yes	No	No	No	No	Yes	No/Yes	Yes/No	No
Habit formation: Short rate falls when surplus-consumption ratio rises <sup>vii</sup>	No	No	No	Yes	Yes	Yes	Yes	No	No/Yes	Yes/No	Yes

<sup>i</sup> See Campbell (1986), Campbell (2003), Campbell (2018).

<sup>ii</sup> See Campbell (1986), Campbell (2003), Campbell (2018).

<sup>iii</sup> See Campbell (2003), Bansal and Yaron (2004), Colacito and Croce (2011), Bansal and Shaliastovich (2013), Campbell (2018).

<sup>iv</sup> See Campbell (2003), Bansal and Yaron (2004), Colacito and Croce (2011), Bansal and Shaliastovich (2013), Campbell (2018).

<sup>v</sup> See Wachter (2013) and Campbell (2018).

<sup>vi</sup> See Campbell and Cochrane (1999), Wachter (2006), Verdelhan (2010), and Campbell (2018).

<sup>vii</sup> See Campbell and Cochrane (1999), Wachter (2006), Verdelhan (2010), and Campbell (2018).