A Quantity-Driven Theory of Term Premiums and Exchange Rates *

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Abstract

We develop a model in which risk-averse, 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 bond term premiums in both currencies, as well as the foreign exchange rate between the two currencies. Our model matches several important empirical patterns, including the co-movement between exchange rates and bond term premiums as well as the finding that central banks' quantitative easing policies impact exchange rates. An extension of our model sheds light on the peristent deviations from covered interest rate parity that have emerged since the 2008 financial crisis.

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1 Introduction

One of the most significant financial market developments since the global financial crisis has been the introduction of quantitative easing (QE) policies—i.e., large-scale purchases of long-term bonds—by the world's major central banks. While there continues to be an active debate about the long-run impact of these policies, the evidence is largely settled that asset purchase programs achieved the intended short-run effect of reducing long-term bond yields (Gagnon et. al. [2011], Joyce et. al. [2011]). More recent empirical work has suggested that quantitative easing policies also impacted foreign exchange rates. For example, Neely (2010), Bauer and Neely (2014), and Swanson (2017) have noted 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.

From the point of view of standard asset pricing theory, making sense of the impact of QE has proven difficult. Ben Bernanke, while Chair of the Federal Reserve, quipped that "the problem with quantitative easing is that it works in practice, but it doesn't work in theory." As Woodford (2012) explains, a mere "reshuffling" of assets between households and the central bank does not change the pricing kernel in standard theories. Addressing this challenge, a growing literature argues that 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. This literature assumes that bond markets are not closely tied to the ultimate household sector and, hence, are often disconnected the kinds of consumption risk considerations featured in standard theories. Instead, specialized bond investors with limited risk tolerance—best thought of as financial intermediaries—must be paid to absorb shocks to the supply and demand for long-term bonds (Vayanos and Vila [2009, 2019], Greenwood and Vayanos [2014]).

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 risk borne by specialized investors.[1] Since the fixed-income market is assumed to be both disconnected from aggregate consumption and partially segmented from other parts of the broader capital markets (e.g., equities), specialized bond investors cannot diversify away the interest rate risk they bear. This segmentation explains why QE policies—which, while large relative to national bond markets, are small relative to global market for all financial assets—have a large impact on long-term yields.

In this paper, we argue that this same quantity-driven, supply-and demand approach is also sheds light on several puzzles in the exchange rate literature, including the impact of QE on foreign exchange (FX) rates. The key idea is that foreign exchange is an "interest-rate sensitive" asset—i.e., it is heavily exposed to news about future short-term interest rates. Thus, if the global bond and FX markets are integrated with one another, shocks to the supply of other rate-sensitive assets such as long-term bonds in each currency will also impact exchange rates. Concretely, when U.S. short-term interest rates rise, foreign currencies typically depreciate against the U.S. dollar for the usual uncovered-interest-rate-parity (UIP) reasons. At the same time, the prices

[1] See, for example, Hamilton and Wu (2012), D'Amico and King (2013), and Greenwood, Hanson, and Vayanos (2016).

of long-term dollar-denominated bonds decline for standard expectations hypothesis reasons. Since foreign currencies and long-term U.S. bonds are exposed to the same primary risk factor—unexpected movements in short-term U.S. interest rates, a shift in the supply of long-term U.S. bonds affects the risk premium on both types of assets.

Our baseline model is a straightforward generalization of the Vayanos and Vila (2009, 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). There is an exogenously given short-term interest rate in each currency that evolves stochastically over time. We assume the 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 foreign 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—a trade that borrows short-term and lends long-term in a given currency—and an "FX trade"—a trade that 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 premiums, 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, consider the U.S. yield curve trade. 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 also 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 a 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 in order 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., 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. At the same time, 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 then be expected to appreciate going forward.[2]

The baseline model makes several additional predictions. First, we show that bond supply shocks should have a larger impact on bilateral exchanges rates when the correlation between the two countries' short rates is low. For example, the USD-JPY exchange rate should be less responsive to U.S. QE than the USD-EUR exchange rate. 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 bond return predictability and foreign exchange return predictability. 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 rates investors' exposure to the FX trade is increasing in the foreign exchange rate due to balance-of-trade driven flows. This assumption, which is needed in Gabaix and Maggiori (2015) to match the Fama (1984) result, immediately delivers in our model the Campbell-Shiller (1991) for both the yield-curve trades in both currencies.[3]

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 bear greater euro exposure when the euro is strong.[4] 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

[2] 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.

[3] Symmetrically, the assumption used by Vayanos and Vila (2009, 2019) to match the Campbell-Shiller (1989) 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.

[4] The idea is that U.S. net exports to Europe rise when the euro is strong and the dollar is weak. U.S. exporters then want to swap the euros they receive from their European sales back into dollars. To accommodate these trade-driven flows, global bond investors must sell dollars and buy euros.

to mean-revert. Thus, the model will also match Campbell and Shiller's (1991) finding that a steep yield curves predicts high excess returns on long-term bonds.

We then extend our model to explore the 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 limited risk-bearing capacity. Therefore, we make two additional assumptions. First, we assume the only market participants 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. Second, we assume risk-averse 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 bond supply shocks generate investor demand to hedge FX risk using FX forwards. Banks accommodate this demand and then hedge the accompanying risk by engaging in CIP arbitrage trades. Since these trade use scare 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.

In our baseline model, global bond and FX markets are partially segmented from other asset classes, but tightly integrated with each other: global bond investors can flexibly buy bonds of any maturity in both currencies. In a second extension, we ask what happens if some bond investors are less flexible, i.e., if there is further segmentation 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 segmentation 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.

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 fundamentals (Obstfeld and Rogoff [2000]) is explained by a disconnect between intermediaries in currency markets and the broader economy.[5] Our paper is also closely related to papers studying portfolio balance effects in bond markets.[6] Our key contribution is to show that the structure of

[5] 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.

[6] See, for example, Vayanos and Vila (2009, 2019), Greenwood, Hanson, and Stein (2010), Greenwood and

financial intermediation, which links shocks hitting the intermediaries in FX markets to shocks in the bond market, helps to explain several important empirical patterns. In the model, we assume that the same intermediaries are the marginal investors in both long-term bond and foreign exchange markets. Given our key observation that both long-term bonds and foreign exchange are interest-rate sensitive assets, this form of segmentation is natural: any human capital or physical infrastructure useful for managing interest-rate sensitive assets can naturally be applied to both bonds and foreign exchange.

The closest paper to ours is contemporaneous work by Gourinchas, Ray, and Vayanos (GRV 2020). They also study a two-currency generalization of the Vayanos and Vila (2009, 2019) term structure model. GRV work in continuous time and focus on demand risk and quantifying the size of the model-implied relationship between term premia and FX premia. In contrast, we work in discrete time and focus on segmentation, FX hedging, and CIP violations.

Our paper is also related to the vast literature taking a consumption-based, representative agent approach to exchange rates.[7] 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 premiums. By contrast, in our model, the correlation is positive. The key difference is that in consumption-based models, domestic long-term bonds are hedges and foreign assets are risky for domestic investors. The reason is that in consumption-based models domestic interest rates fall and domestic currency appreciates in bad domestic times. Thus, domestic long-term bonds rise in value and foreign assets fall in value from the perspective of domestic investors. In contrast, in our model, as in the data, both domestic interest rates and domestic currency both fall in bad domestic times.

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 the persistent deviations from covered-interest-rate parity that have been witnessed since the 2008 financial crisis. 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.

2 Motivating evidence

To motivate our theoretical analysis, we begin by presenting 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

Vayanos (2014), Hanson (2014), Hanson and Stein (2015), Malkhozov, Mueller, Vedolin, and Venter (2016), Hanson, Lucca, and Wright (2018), and Haddad and Sraer (2019).

[7]Prominent 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), and Farhi and Gabaix (2016).

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, the differences in term premiums 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 such as QE are just "reshufflings" in the sense of Woodford (2012) and have no effect on asset prices.

2.1 Contemporaneous movements in foreign exchange rates

Table 1 shows monthly panel regressions of the form

$$\Delta_h q_{c,t} = A_c + B \times \Delta_h \left(i^*_{c,t} - i_t\right) + D \times \Delta_h \left(y^*_{c,t} - y_t\right) + \Delta_h \varepsilon_{c,t}, \tag{1}$$

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 yield and long-term interest rate as the 10-year zero-coupon government yield. Details on data construction are in the Online Appendix. The regressions include currency fixed effects and exploit within currency time-series variation. The regressions are estimated using monthly data and contain overlapping observations, so we report Driscoll-Kraay (1998) standard errors—which are the panel analog of Newey-West (1987).

Column (1) shows the well-known result, consistent with standard uncovered interest rate parity (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 short- and long-term rate differentials into their foreign and U.S. dollar components:

$$\Delta_h q_{c,t} = A_c + B_1 \times \Delta_h i^*_{c,t} + B_2 \times \Delta_h i_t + D_1 \times \Delta_h y^*_{c,t} + D_2 \times \Delta_h y_{c,t} + \Delta_h \varepsilon_{c,t}. \tag{2}$$

Foreign and U.S. short-term rates enter with opposite signs in column (3).[8] 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 term premium differentials impact the exchange rate.

[8] 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, we might expect this result if we think of the U.S. as setting world short rates and the short rates in other currencies 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 $\beta^*_c \in (0, 1)$.

Columns (5) to (8) repeat the analysis from columns (1) to (4), but in this case the dependent variable is the annual change in the exchange rate. 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 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, which compares to a coefficients of 3.51 and 4.37 in column (2) of Table 1. Thus, Table 2 reinforces the conclusion that changes in the term premia 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 for this sample dependence is that inflation was more volatile in earlier periods. As emphasized in Section 3, 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 exchanges rates and bond term premia if bond markets are highly segmented from the foreign exchange market.

A final concern is that our results may reflect an omitted variables problem to the extent that changes in long-term yields and foreign exchange rates reflect common movements in money-like, convenience premiums as in Krishnamurthy and Vissing-Jorgensen (2012) and Jiang, Krishnamurthy, and Lustig (2019). Convenience premiums are also quantity-driven, but are conceptually distinct from the bond risk premiums that are our focus. However, fluctuations in convenience premiums should generate the opposite relationship between contemporaneous changes in foreign exchange rates and U.S. Treasury yields.[9] Thus, when we control for the innovation to Jiang, Krishnamurthy, and Lustig's (2019) U.S. Treasury basis variable—which indeed helps explain contemporaneous movements in exchange rates—the coefficients of interest in Tables 1 and 2 are essentially unchanged.

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 bond return regressions of the form

$$rx^{y*}_{c,t\to t+h} - rx^{y}_{t\to t+h} = A_c + B \times \left(i^*_{c,t} - i_t\right) + D \times \left(f^*_{c,t} - f_t\right) + \varepsilon_{c,t\to t+h}, \tag{3}$$

and

$$rx^{y*}_{c,t\to t+h} - rx^{y}_{t\to t+h} = A_c + B_1 \times i^*_{c,t} + B_2 \times i_t + D_1 \times f^*_{c,t} + D_2 \times f^*_t + \varepsilon_{c,t\to t+h}. \tag{4}$$

Here $rx^{y*}_{c,t\to t+h}$ denotes h-month returns on long-term bonds in country c in excess of the short-term interest rate in that country. $rx^{y}_{t\to t+h}$ denotes h-month excess returns on long-term bonds in the U.S. As in Tables 1 and 2, the sample period run 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, then, over the next three months, the excess returns (in foreign currency) on long-term foreign bonds exceed the 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

[9] Suppose there is an increase in the supply of U.S. Treasury debt. Assuming the special demand for U.S. Treasury debt is downward sloping, this supply increase will lower the convenience premium on U.S. Treasuries, pushing up U.S. Treasury yields (Krishnamurthy and Vissing-Jorgensen [2012]). Furthermore, if foreign investors derive greater convenience services from U.S. Treasuries than do U.S. investors, this increase in U.S. Treasury supply should also lead the dollar to depreciate versus foreign currencies—i.e., foreign currencies should appreciate versus the dollar. Thus, movements in convenience premium should lead to a positive association between contemporaneous movements in U.S. Treasury yields and movements in foreign currencies.

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:

$$rx^q_{c,t\to t+h} = A_c + B \times \left(i^*_{c,t} - i_t\right) + D \times \left(f^*_{c,t} - f_t\right) + \varepsilon_{c,t\to t+h}, \tag{5}$$

and

$$rx^q_{c,t\to t+h} = A_c + B_1 \times i^*_{c,t} + B_2 \times i_t + D_1 \times f^*_{c,t} + D_2 \times f_t + \varepsilon_{c,t\to t+h}, \tag{6}$$

where $rx^q_{c,t\to t+h} \equiv q_{c,t+h} - q_{c,t} + (h/12) \times (i^*_{c,t} - i_t)$ is the h-month excess return (in dollars) on the 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).[10] This means that if the foreign distant forward rate rises by one percentage point relative to the U.S. distant forward, 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, Tables 2 show 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 a high foreign-minus-U.S. distant forward rate differential is associated with subsequent depreciation of the foreign currency and thus low returns on foreign currency.

2.3 Central bank quantitative easing announcements

Our results so far are consistent with the idea that bond term premiums play a role in driving the foreign exchange risk premium. That said, our prior results do not tell us precisely what drives bond term premiums 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 premiums, and show that these changes in term premiums 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

[10] The coefficients on the short-term interest rate differential are 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]).

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 interest 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 approximately 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 the 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:

$$\Delta_4 q_{c,t+2} = A + B \times \left(\Delta_4 i^*_{c,t+2} - \Delta_4 i_{t_{t+2}}\right) + D \times \left(\Delta_4 f^*_{c,t+2} - \Delta_4 f_{t+2}\right) + \Delta_4 \varepsilon_{c,t+2}, \tag{7}$$

and

$$\Delta_4 q_{c,t+2} = A + B_1 \times \Delta_4 i^*_{c,t+2} + B_2 \times \Delta_4 i_{t_{t+2}} + D_1 \times \Delta_4 f^*_{c,t+2} + D_2 \times \Delta_4 f_{t+2} + \Delta_4 \varepsilon_{c,t+2}. \tag{8}$$

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, the United Kingdom, 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 premiums 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-market term premiums and FX risk premiums, but that both of these premiums 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 (2009, 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 demand shocks in the foreign exchange market. These specialists have a risk-bearing capacity that is potentially small relative to the supply-and-demand shocks they must absorb and are concerned about the risk of near-term losses on their imperfectly diversified portfolios. As a result, they will only absorb these shocks if the expected returns on domestic and foreign long-term bonds as well as foreign exchange adjust in response.[11]

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 impact the qualitative conclusions we draw.[12]

3.1.1 Financial assets

Here we describe the four assets in the model: short- and long-term bonds in both domestic and foreign 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. We think of the short-term domestic rate as being determined outside the model by domestic monetary policy. 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.[13]

[11] To be clear, we are not assuming that global financial markets are highly segmented: we are simply positing that there is some segmentation at the level of broad financial asset classes. In other words, we are assuming 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.

[12] This approach is also used Greenwood, Hanson, and Liao (2018) and Hanson, Lucca, and Wright (2018).

[13] One interpretation of this assumption is that the only short-term debt instruments in each currency are short-term interest-bearing deposits. The domestic and foreign central banks independently pursue monetary

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:

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

where y_t is the log yield-to-maturity on domestic bonds and $\delta \in (0,1)$.[14] 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, $-\left(\delta/\left(1-\delta\right)\right)\left(y_{t+1} - y_t\right)$, due to changes in yields.

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

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

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., a 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). We use $rx_{t+1}^{y^*} \equiv r_{t+1}^{y^*} - i_t^*$ to denote 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:

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

policy in their currencies by posting an interest rate and then elastically borrowing and lending at that rate.

[14] 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* $r_{t+1}^n = y_t^n - (n-1)\left(y_{t+1}^{n-1} - y_t^n\right)$ where, for instance, y_t^n is the log yield on n-period zero-coupon bonds at t.

Thus, the excess return on foreign currency is the sum of a "carry" component, $i_t^* - i_t$, that investors earn if exchange rates do not change and a capital gain component, $(q_{t+1} - q_t)$, due to changes in exchange rates. Assuming the exchange rate is stationary with a steady-state level of $q_t = 0$—i.e., that purchasing-power parity holds in the long run, we can iterate forward and take expectations to obtain:

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

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

Although UIP fails in our baseline model, covered-interest-rate parity (CIP) must hold in our baseline model because (i) the only friction is the limited risk-bearing capacity of bond investors and (ii) the CIP arbitrage trade is completely riskless—i.e., violations of CIP are failures of the Law of One Price. However, in Section 4, we will model the kinds of post-2008 CIP violations documented by Du, Tepper, and Verdelhan (2018) and Jiang, Krishnamurthy, and Lustig (2019) using a combination of market segmentation and non-risk-based balance sheet constraints.

Real versus nominal rates Since our theory hinges on comovement between exchange rates and short-term interest rates, it makes sense to think of the four interest rates in our model as real interest rates and the exchange rate as the real exchange rate.[15] This is why we focused on data in recent decades—when inflation expectations have been firmly anchored and where movements in nominal interest rates largely correspond to movements in real rates—in the previous section.

3.1.2 Risk factors

Investors face two types of risk in our model: interest rate risk and supply risk. First, long-term bonds are exposed to interest rate risk. For example, long-term domestic bonds will suffer an unexpected loss if short-term domestic rates rise unexpectedly. Similarly, foreign exchange positions are exposed to interest rate risk: foreign currency will depreciate (appreciate) unexpectedly if short-term domestic (foreign) rates rise unexpectedly. Second, both long-term bonds and FX positions are exposed to supply risk: there are random supply shocks which 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. Specifically, we assume:

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

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

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

[15] If short-term nominal interest rates move one-for-one with expected inflation, then news about future inflation will not impact real exchange rates. What is more, inflation news will not lead to *unexpected* changes in *nominal* exchange rates: it will only lead to expected future movements in nominal exchange rates. By contrast, news about future short-term real rates should always impact both real and nominal exchange rates.

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:

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

where $\bar{s}^y > 0$, $\phi_{s^y} \in [0,1)$, and $Var_t[\varepsilon_{s_{t+1}^y}] = Var_t[\varepsilon_{s_{t+1}^{y*}}] = \sigma_{s^y}^2 \geq 0$. 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 rates investors must absorb in equilibrium. Assuming that the two short rates and bond supplies follow symmetric AR(1) processes enhances the analytical tractability of the model, but it is easy to solve the model numerically if we relax these symmetry assumptions.[16]

Net FX supply We assume that global bond investors must engage in a borrow-at–home and lend-abroad FX trade in time-varying market value (in domestic currency units) s_t^q to accommodate the opposing demand of other unmodeled agents.[17] Concretely, we assume:

$$s_{t+1}^q = \phi_{s^q} s_t^q + \varepsilon_{s_{t+1}^q}, \tag{15}$$

where $Var_t[\varepsilon_{s_{t+1}^q}] = \sigma_{s^q}^2 \geq 0$ and $\phi_{s^q} \in [0,1)$. 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. Again, this independence assumption enhances analytical tractability, but it is straightforward to solve the model numerically for any arbitrary variance-covariance matrix $\boldsymbol{\Sigma}$.

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 a constant risk tolerance of τ and have mean-variance preferences over wealth tomorrow. 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-at-home and lend-abroad FX trade, all denominated

[16]The Appendix discusses the impact of relaxing these symmetry assumptions on short rates and bond supply.

[17]When we consider violations of CIP in Section 4, we will separately consider outside demand for spot and forward FX transactions. In this section, where CIP holds, s^q should be thought of as "uncovered" spot transactions, i.e., spot transactions that are not FX-hedged in the forward market.

in domestic currency.[18] Thus, defining $\mathbf{d}_t \equiv [d_t^y,\ d_t^{y*},\ d_t^q]'$ and $\mathbf{rx}_{t+1} \equiv [rx_{t+1}^y,\ rx_{t+1}^{y*},\ rx_{t+1}^q]'$, investors choose their holdings to solve

$$\max_{\mathbf{d}_t} \left\{ \mathbf{d}_t' E_t [\mathbf{rx}_{t+1}] - \frac{1}{2\tau} \mathbf{d}_t' Var_t [\mathbf{rx}_{t+1}] \mathbf{d}_t \right\}, \tag{16}$$

so their demands must satisfy:

$$E_t [\mathbf{rx}_{t+1}] = \tau^{-1} Var_t [\mathbf{rx}_{t+1}] \mathbf{d}_t. \tag{17}$$

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 highly interest-rate sensitive assets. Specifically, 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.[19]

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 5×1 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

[18] We assume global bond investors solve (16) irrespective of whether they are domestic- or foreign-based. The idea is that we can represent an investor's positions in any asset other than short-term bonds in her local currency as a linear combination of these three long-short trades. So, assuming all investors have the same risk tolerance *in domestic 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 whether they are based at home or abroad. In particular, investors are always free to hedge any FX exposure stemming from investments in long-term bonds in non-local currency. As a result, they will only take on FX exposure if they are rewarded for doing so. (Technically, since all investors have the same constant risk tolerance τ in domestic currency terms, we are assuming that the risk tolerance of any foreign-based investors is τ/Q_t in foreign-currency terms.)

[19] It is easy to allow for shocks to the aggregate risk tolerance of global bond investors. Specifically, if aggregate risk tolerance at time t is τ_t, demands satisfy $E_t [\mathbf{rx}_{t+1}] = \tau_t^{-1} Var_t [\mathbf{rx}_{t+1}] \mathbf{d}_t$. If the *physical* net supply of assets that investors must hold is $\hat{\mathbf{s}}_t$, the market-clearing conditions are $\mathbf{d}_t = \hat{\mathbf{s}}_t$, implying $E_t [\mathbf{rx}_{t+1}] = Var_t [\mathbf{rx}_{t+1}] \tau_t^{-1} \hat{\mathbf{s}}_t$. This is equivalent to our model with $\tau = 1$ and $\mathbf{s}_t = \tau_t^{-1} \hat{\mathbf{s}}_t$. We would then assume the effective supplies $\mathbf{s}_t = \tau_t^{-1} \hat{\mathbf{s}}_t$ follow a VAR(1) process with correlated shocks which capture these common underlying movements in τ_t.

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 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 τ is sufficiently large relative to the volatility of supply shocks and (ii) the model admits multiple equilibria.[20] 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.[21] We focus on the 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:

$$E_t\left[\mathbf{rx}_{t+1}\right] = \tau^{-1} Var_t\left[\mathbf{rx}_{t+1}\right]\mathbf{s}_t = \tau^{-1}\mathbf{V}\mathbf{s}_t, \tag{18}$$

where $\mathbf{V} = Var_t\left[\mathbf{rx}_{t+1}\right]$ 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:

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

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

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

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.

[20] Equilibrium non-existence and multiplicity of this sort are common in models like ours where short-lived investors absorb shocks to the supply of infinitely-lived assets. Different equilibria correspond to different self-fulfilling beliefs that investors hold about the price-impact of supply shocks and, hence, the risks associated with holding assets. 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).

[21] Consistent with Samuelson's (1947) "correspondence principle," this 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 unique stable equilibrium, an increase in the volatility of short rate shocks always increases the impact of supply shocks on equilibrium prices. Furthermore, as supply risk grows small, the stable equilibrium converges to the equilibrium with no supply risk, whereas the unstable equilibria explode with extremely small supply shocks having a massive price impact.

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:

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

the long-term foreign yield is:

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

and the foreign exchange rate is

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

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. For instance, the expectations hypothesis component of long-term domestic rates depends on the current deviation of short-term domestic rates from their steady-state level $(i_t^* - \bar{\imath})$ and the persistence of short-term rates (ϕ_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 an uncovered interest rate parity (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-at-home lend-abroad 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:

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

where, for $f \in \{i, i^*, s^y, s^{y*}, s^q\}$, β^a_f 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.[22] 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:

$$\lambda_{i,t} = \tau^{-1}\sigma_i^2 \times \sum_a \left[(\beta^a_i + \rho\beta^a_{i^*}) \times s^a_t\right], \tag{22a}$$
$$\lambda_{i^*,t} = \tau^{-1}\sigma_i^2 \times \sum_a \left[(\rho\beta^a_i + \beta^a_{i^*}) \times s^a_t\right], \tag{22b}$$

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

$$\lambda_{f,t} = \tau^{-1}\sigma_f^2 \times \sum_a [\beta^a_f \times s^a_t]. \tag{22c}$$

Expected returns can also be written using a "conditional-CAPM" representation.[23] Specifically, letting $rx^{s_t}_{t+1} = \mathbf{s}'_t \mathbf{rx}_{t+1}$ denote the excess return on global bond investors' portfolio from t to $t+1$, the conditional expected return on any asset $a \in \{y, y^*, q\}$ is:

$$E_t\left[rx^a_{t+1}\right] = \frac{Cov_t[rx^a_{t+1}, rx^{s_t}_{t+1}]}{Var_t[rx^{s_t}_{t+1}]} \times E_t[rx^{s_t}_{t+1}]. \tag{23}$$

Thus, the expected return on each asset equals its conditional β with respect to the return on the portfolio held by bond investors times the conditional expected return on that portfolio. 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 the three asset returns 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 market portfolio consisting of all global financial wealth.

3.3 Bond term premiums 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 $\sigma^2_{s^y} = \sigma^2_{s^q} = 0$.

[22] Formally, β^a_f is the coefficient on $\varepsilon_{f_{t+1}}$ from a multivariate regression of $-(rx^a_{t+1} - E_t[rx^a_{t+1}])$ on the innovations to the five risk factors—i.e., we have $rx^a_{t+1} - E_t[rx^a_{t+1}] = -\beta^a_i \varepsilon_{i_{t+1}} - \beta^a_{i^*}\varepsilon_{i^*_{t+1}} - \beta^a_{s^y}\varepsilon_{s^y_{t+1}} - \beta^a_{s^{y*}}\varepsilon_{s^{y*}_{t+1}} - \beta^a_{s^q}\varepsilon_{s^q_{t+1}}$. Thus, the prices of factor risk ($\lambda_{f,t}$) are non-negative in the model's steady-state.

[23] An analogous result obtains in many segmented-market asset pricing models, including Gabaix, Krishnamurthy, and Vigneron (2007), Garleanu, Pedersen, and Poteshman (2009), and Vayanos and Vila (2009, 2019).

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

$$C_{y,q} = (1-\rho)\frac{\delta}{1-\delta\phi_i}\frac{1}{1-\phi_i}\sigma_i^2 > 0. \tag{24}$$

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

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

Proposition 1 provides guidance about how shifts in long-term bond supply—e.g., due to QE policies—should impact exchange rates and term premiums. There are two key takeaways.[24]

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 (2009, 2019). The increase in dollar bond supply also raises the euro term premium and euro long-term yields when $\rho > 0$.[25] 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 has risen, 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.[26]

Second, Proposition 1 shows that the effects of a shift in domestic bond supply depend on the correlation ρ between domestic and foreign short-rates. When ρ 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 those in Europe than those in Japan. 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 Japanese yen than versus the euro. At the same time, U.S. QE should lead to a larger reduction in European term premia than Japanese term premia. Intuitively, if foreign and domestic short rates are highly correlated, then 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

[24] Technically, the comparative statics in Proposition 1 must be interpretted 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.

[25] This occurs even though long-term euro yields are not *directly* exposed to movements in dollar short rates. Specifically, when $\rho > 0$, an increase in dollar bond supply raises the price of euro short-rate risk in Eq. (22b). Intuitively, since the euro yield-curve trade tends to suffer at the same time as the dollar yield-curve trade, an increase in the supply of dollar bonds raises the expected return on the euro yield-curve trade.

[26] 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 $\partial E_t[rx_{t+1}^q]/\partial s_t^y > 0$.

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.

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.[27]

Proposition 2 ***Equilibrium with supply shocks.*** *If $0 \leq \rho < 1$, $\sigma^2_{s^y} \geq 0$, $\sigma^2_{s^q} \geq 0$, then in any stable equilibrium we have $\partial E_t[rx^q_{t+1}]/\partial s^y_t = \tau^{-1} C_{y,q} > 0$. If in addition $\rho > 0$ and $\sigma^2_{s^q} = 0$, then in any stable equilibrium we have $\partial E_t[rx^{y*}_{t+1}]/\partial s^y_t = \tau^{-1} C_{y,y*} > 0$. Thus, by continuity of the stable equilibrium in the model's underlying parameters, we have $\partial E_t[rx^{y*}_{t+1}]/\partial s^y_t > 0$ unless foreign exchange supply shocks are especially volatile and ρ 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 ($\sigma^2_{s^q}$ is large) and the correlation of short rates ρ 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 ρ 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 $s^q_t = 0$ and $\sigma^2_{s^q} = 0$.[28] In this case, the foreign exchange risk premium is decreasing in the difference between foreign and domestic bond supply ($s^{y*}_t - s^y_t$),

$$E_t\left[rx^q_{t+1}\right] = \overbrace{\left[-\tau^{-1} C_{y,q}\right]}^{<0} \times \left(s^{y*}_t - s^y_t\right), \tag{26}$$

[27] As shown in the Online Appendix, when $\sigma^2_{s^y} > 0$ and $\sigma^2_{s^q} > 0$, solving the model involves characterizing the stable solution to a system of four quadratic equations in four unknowns. When $\sigma^2_{s^y} > 0$ and $\sigma^2_{s^q} = 0$, the model can be solved analytically: we simply need to solve two quadratics and a linear equation.

[28] The Online Appendix shows that a similar, albeit slightly more complicated, set of results obtains when $\sigma^2_{s_q} > 0$ and $s^q_t \neq 0$.

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

$$E_t\left[rx_{t+1}^{y*} - rx_{t+1}^{y}\right] = \overbrace{\left[\tau^{-1}\left(V_y - C_{y,y^*}\right)\right]}^{>0} \times \left(s_t^{y*} - s_t^{y}\right). \tag{27}$$

Eqs. (26) and (27) 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. (27) shows that this decline in euro bond supply should reduce euro term premia relative to dollar term premia. And, Eq. (26) shows that this decline in s_t^{y*} should increase the risk premium on the borrow-in-dollar lend-in-euros FX trade, 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. (26) and (27), the FX risk premium is negatively related to the difference between foreign and domestic bond risk premia:

$$E_t\left[rx_{t+1}^{q}\right] = \overbrace{\left[-\frac{C_{y,q}}{V_y - C_{y,y^*}}\right]}^{<-1} \times E_t\left[rx_{t+1}^{y*} - rx_{t+1}^{y}\right]. \tag{28}$$

Eq. (28) motivates the tests 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-dollar lend-in-euro 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—i.e., the FX risk premium moves proportionately with the domestic term premium.[29]

Combining Eq. (12) and (28), the exchange rate reflects the sum of expected (i) foreign-minus-domestic short rate differentials and (ii) foreign-minus-domestic bond risk-premium differentials:

$$q_t = \textstyle\sum_{j=0}^{\infty} E_t[i_{t+j}^{*} - i_{t+j}] + \overbrace{\left[\frac{C_{y,q}}{V_y - C_{y,y^*}}\right]}^{>1} \times \textstyle\sum_{j=0}^{\infty} E_t[rx_{t+j+1}^{y*} - rx_{t+j+1}^{y}]. \tag{29}$$

This result motivates the tests in Table 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.

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 in the currency with low rates and lends long-term in the currency with high rates. To see this, note that the

[29] The constant of proportionality in Eq. (28), $-C_{y,q}/\left(V_y - C_{y,y^*}\right)$, is less than -1 because foreign exchange is effectively a "longer duration" asset than long-term bonds.

return on a long-term FX trade that borrows long-term at 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 at home ($-rx^y_{t+1}$), plus (ii) the return to borrowing short at home to lend short abroad (rx^q_{t+1}), plus (iii) the return to borrowing short abroad to lend long abroad (rx^{y*}_{t+1}). Thus, the expected return on the long-term FX trade is:

$$E_t\left[rx^q_{t+1} + \left(rx^{y*}_{t+1} - rx^y_{t+1}\right)\right] = \overbrace{\left[1 - \frac{V_y - C_{y,y^*}}{C_{y,q}}\right]}^{\in(0,1)} \times E_t\left[rx^q_{t+1}\right]. \tag{30}$$

Eq. (30) 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 rates investors as compared to the standard FX trade. For instance, the standard FX trade (rx^q_{t+1}) will suffer when there is an unexpected increase in domestic short rates. However, borrowing-long to lend-short in domestic currency (i.e., $-rx^y_{t+1}$) will profit when there is an unexpected rise in domestic 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 that on the standard short-term FX trade.

We collect these observations in the following proposition:

Proposition 3 ***Empirical implications.*** *Suppose $\rho \in (0,1)$, $\sigma^2_{s^y} > 0$, and $\sigma^2_{s^q} = 0$. Then:*

- *The FX risk premium ($E_t\left[rx^q_{t+1}\right]$) is decreasing in the difference in net long-term bond supply between foreign and domestic currency ($s^{y*}_t - s^y_t$). The difference between foreign and domestic bond risk premia, $E_t\left[rx^{y*}_{t+1} - rx^y_{t+1}\right]$, is increasing in $s^{y*}_t - s^y_t$.*
- *$E_t\left[rx^q_{t+1}\right]$ is negatively related to $E_t\left[rx^{y*}_{t+1} - rx^y_{t+1}\right]$.*
- *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 ($E_t\left[rx^q_{t+1} + \left(rx^{y*}_{t+1} - rx^y_{t+1}\right)\right]$) is smaller in magnitude than that on the standard borrow-short-in-domestic to lend-short-in-foreign FX trade, ($E_t\left[rx^q_{t+1}\right]$).*

3.4 A unified approach to carry trade returns

In this subsection, we show that our model can deliver a unified explanation that links foreign exchange return predictability and bond return predictability. For foreign exchange, Fama (1984) showed that the expected return on the borrow-at-home to lend-abroad FX trade is increasing in the foreign-minus-domestic short rate differential, $i^*_t - i_t$. This is the best known and most empirically robust failure of uncovered interest rate parity. 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 or the "term spread," $y_t - i_t$. This is arguably the best known and most empirically robust failure of the expectations hypothesis of the term structure. In other words, the expected excess returns on both the FX trade and the yield curve trade are increasing in their "carry," defined as the return that investors will earn if asset prices remain unchanged.

The baseline model we developed above does not generate either the Fama (1984) result for the FX trade or the Campbell and Shiller (1991) result for the yield curve trade. In our baseline model, shocks to short-term interest rates make foreign exchange and long-term bonds risky investments for global rates investors. However, the level of short-term interest rates does not affect expected excess returns on foreign exchange 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 rates 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) needed to make to match the Fama (1984) pattern within a segmented-markets model of the foreign exchange market, immediately delivers the Campbell-Shiller (1991) result for both the domestic and foreign yield-curve trades. Symmetrically, the assumption that Vayanos and Vila (2009, 2019) needed to make to match the Campbell-Shiller (1991) fact within a segmented-markets model of the term structure—i.e., 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:

$$n_t^y = s_t^y - S_y y_t, \tag{31a}$$

$$n_t^{y*} = s_t^{y*} - S_y y_t^*, \tag{31b}$$

$$n_t^q = s_t^q + S_q q_t, \tag{31c}$$

where S_q, $S_y \geq 0$. In words, we assume the net supply of each asset is increasing that asset's price—either because gross supply is increasing in price or because the demand of preferred habitat investors is decreasing in 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 the home country runs a trade surplus of $S_q q_t$ with the foreign country: when foreign currency is strong, home exports rise and imports fall. However, if the home 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. As Gabaix and Maggiori (2015) show, assuming that $S_q > 0$ in this way delivers the Fama (1984) result for foreign exchange markets.

We solve the extended model using the same approach that we used to solve the baseline model.[30] The comparative statics of expected returns with respect to the independent supply shocks—s_t^y, s_t^{y*}, and s_t^q— in this extension are similar to those in the baseline model. However, in this extension, i_t and i_t^* impact now expected returns on the three carry trades.

Proposition 4 ***Matching Fama (1984), Campbell-Shiller (1991), and Lustig, Stathopoulos, and Verdelhan (2019).*** *Suppose $\rho < 1$. 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 $\partial E_t\left[rx_{t+1}^q\right]/\partial i_t^* = -\partial E_t\left[rx_{t+1}^q\right]/\partial i_t > 0$. Since exchange rates are less responsive to short rates than under UIP, if one estimates the time-series regression:*

$$rx_{t+1}^q = \alpha_q + \beta_q \times (i_t^* - i_t) + \xi_{t+1}^q, \tag{32}$$

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 $\partial E_t\left[rx_{t+1}^y\right]/\partial i_t = \partial E_t\left[rx_{t+1}^{y*}\right]/\partial i_t^* < 0$. 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:

$$rx_{t+1}^y = \alpha_y + \beta_y \times (y_t - i_t) + \xi_{t+1}^y \quad \text{and} \quad rx_{t+1}^{y*} = \alpha_{y*} + \beta_{y*} \times (y_t^* - i_t^*) + \xi_{t+1}^{y*}, \tag{33}$$

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

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

$$rx_{t+1}^q + \left(rx_{t+1}^{y*} - rx_{t+1}^y\right) = \alpha_{q,lt} + \beta_{q,lt} \times (i_t^* - i_t) + \xi_{t+1}^{q,lt}, \tag{34}$$

one obtains $0 < \beta_{q,lt} < \beta_q$ as in Lustig, Stathopoulos, and Verdelhan (2019).

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

$$E_t\left[rx_{t+1}^q\right] = \tau^{-1}\left[C_{y,q}S_y \times (y_t^* - y_t) + V_q \times S_q q_t\right], \tag{35}$$

and

$$E_t\left[rx_{t+1}^y - rx_{t+1}^{y*}\right] = \tau^{-1}\left[\left(V_y - C_{y*,y}\right)S_y \times (y_t^* - y_t) + 2C_{y,q}S_q \times q_t\right]. \tag{36}$$

First, assume $S_q > 0$ and $S_y = 0$ and suppose that $i_t^* - i_t > 0$—i.e., that 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 U.S. net exports will be high, so U.S. exporters will want to convert their euro sales back to dollars. The need to absorb these trade-driven FX flows means that global bond investors must bear greater exposure to the

[30] Specifically, the demands $\mathbf{d}_t$ of global rates investors are still given by Eq. (17) above. Stacking the net supplies in Eq. (31) as $\mathbf{n}_t = \left[n_t^y, n_t^{y*}, n_t^q\right]'$, the market clearing conditions become $\mathbf{d}_t = \mathbf{n}_t$. Thus, equilibrium returns satisfy $E_t\left[\mathbf{rx}_{t+1}\right] = \tau^{-1}Var_t\left[\mathbf{rx}_{t+1}\right]\mathbf{n}_t$.

euro when the euro is strong, raising 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 euro-minus-dollar short-rate differential as in Fama (1984). This mechanism allows Gabaix and Maggiori (2015) to match the Fama (1984) result. However, because these FX exposures mean that global bond investors will lose (make) money if dollar (euro) short rates rise, the equilibrium expected returns on the dollar (euro) yield curve trade must also rise (fall). Since the U.S. term structure will steeper when $i_t^* - i_t > 0$ by standard expectations-hypothesis logic, the extended model will match Campbell and Shiller's (1991) finding that a steep yield curve predicts high excess returns on long-term bonds.[31] Finally, due to the negative relationship between the short-term interest rates and bond risk 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 one borrows long-term in currencies with low interest rates to lend long-term in currencies with high rates.[32]

Another way to simultaneously match these two facts within our model is to follow Vayanos and Vila (2009, 2019) who 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 (2009, 2019) show, assuming that $S_y > 0$ 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 term premium component of long-term yields will be larger in dollars than in euros, matching Campbell-Shiller (1991). However, the resulting difference between dollar and euro long-term bond supply means that global bond investors will have a larger exposure to dollar short-rate shocks, so 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.

3.5 Relationship to consumption-based models

Our quantity-driven, segmented-markets model provides a unified way to understand term premiums and exchange rates. Table 6 compares our model's implications with those of leading frictionless, consumption-based asset pricing models.

Empirically, short-term real interest rates typically rise in economic expansions and fall in recessions—central banks usually set nominal short rates procyclically and nominal prices are

[31] Term spreads also positively forecast bond returns in our baseline model since supply shocks move yields and expected returns on long-term bonds in the same direction. What is novel here is that term spreads forecast bond returns even in the absence of independent supply shocks.

[32] Indeed, we have $\lim_{\delta \to 1} \beta_{q,lt} = 0$. In other words, as the duration of long-term bonds grows without bound ($\delta \to 1$), the expected return on the long-term FX carry trade is independent of the differential in short-term interest rates, $i_t^* - i_t$.

sticky. This means that while economic expansions are good times for the typical household, they are actually bad times for bond investors, who suffer capital losses on their long-term bond holdings at such times. Thus, as in Vayanos and Vila (2009, 2019), long-term bonds are risky for specialized investors, and real term premiums are positive in our model. In contrast, in most consumption-based models, long-term real bonds are a macroeconomic hedge for the representative household, implying that real term premiums are negative.[33] Empirically, both real term and nominal structures are usually upward sloping.[34]

Consumption-based models also imply different patterns of comovement between exchange rates and real interest rates than our model. In consumption-based models, foreign currency appreciates in bad times for foreign agents. This make domestic assets risky for foreign agents. Similarly domestic currency appreciates in bad home times, making foreign assets risky for domestic agents. These patterns rationalize imperfect international risk sharing with complete financial markets. However, since long-term bonds are hedge assets in consumption-based models, this implies that realized foreign currency returns are positively correlated with long-term foreign bond returns and negatively correlated with long-term domestic bond returns. As a result, in most consumption-based models, the FX risk premium is increasing in the foreign-minus-domestic term premium differential (i.e., $E_t[rx^q_{t+1}]$ is positively related to $E_t[rx^{y*}_{t+1} - rx^y_{t+1}]$).

By contrast, in our theory and in the data, 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.

Finally, our model is capable of jointly matching the Fama (1984) forecasting result for foreign exchange and the Campbell-Shiller (1991) forecasting result for long-term bonds. While consumption-based models are capable of matching the Fama (1984) result (see, e.g., Verdelhan [2010] and Bansal and Shaliastovich [2012]), they struggle to simultaneously match the Campbell-Shiller (1991) pattern. 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-term 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 premiums 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

[33] 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.

[34] The U.S. real curve has been upward sloping over 90% of the time from 1999 to present. The U.K. real curve has been upward sloping nearly 75% of the time since 1986. Similar figures for apply for the nominal curve.

spread and bond risk premiums, contrary to Campbell-Shiller (1991).[35] The same is true for Bansal and Shaliastovich (2012), a long-run risks model of foreign exchange.

In summary, Table 6 shows that our model is able to simultaneously match a large number of important stylized facts about long-term bonds and foreign exchange rates. By contrast, leading consumption-based models struggle to simultaneously match these patterns.

4 Deviations from covered-interest-rate parity

In this section, we extend our model to explore violations of covered-interest-rate parity (CIP), which have recently been documented by Du, Tepper, and Verdelhan (2018) and Jiang, Krishnamurthy, and Lustig (2019).[36] To do so, we introduce 1-period foreign exchange forward contracts. When CIP holds, the short-term domestic "cash" rate equals the "synthetic" domestic short rate, 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 two key assumptions. First, 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.

Second, we assume that risk-averse bond investors—who are either domiciled at home or abroad—must use FX forwards if they want to make FX-hedged investments in non-local long-term bonds. This is equivalent to saying that bond investors cannot directly borrow (i.e., obtain "cash" funding) in their non-local currency. They can of course convert 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. Specifically, they can construct synthetic non-local funding by borrowing in local currency, converting this to non-local currency in the spot market, and then forward selling non-local currency in the forward market. We also assume that these bond investors must use FX forwards if they want to make investments in non-local currency.

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 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., there are deviations from CIP.

[35] It is also possible to calibrate the Verdelhan (2010) model to match the Campbell-Shiller (1991) pattern, but one then needs the yield curve to be flatter (less inverted) when short rates are low, which is counterfactual.

[36] We thank Wenxin Du for helpful conversations on this topic.

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 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 and 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, in our model, deviations from CIP are driven by supply-and-demand shocks in the global bond market.

Forward foreign exchange rates Let F_t^Q denote the 1-period forward FX 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 a gross rate of I_t. Second, investors can convert domestic currency into $1/Q_t$ units of foreign currency at t, invest that foreign currency in short-term foreign bonds at rate I_t^*, and enter into an forward contact to exchange foreign for domestic currency at $t+1$, obtaining $F_t^q I_t^*/Q_t$ 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, we have a non-zero "cross-currency basis", x_t^{cip}, given by:

$$x_t^{cip} = i_t - \left(i_t^* + f_t^q - q_t\right). \tag{37}$$

The cross-currency basis, x_t^{cip}, is the domestic 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:

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

Thus, x_t^{cip} is positive when the forward FX rate is lower than is implied by CIP.[37] In this section, we add the riskless log return to CIP arbitrage, x_t^{cip}, to the set of expected excess returns that must be pinned down in equilibrium.

[37] The cross-currency basis, x_t^{cip}, can also be interpretted as the riskless log return a bank earns by executing a 1-period "FX swap" with a customer. In a 1-period FX swap, a bank exchanges foreign for domestic currency at today's spot rate (Q_t) and simultaneously agrees to exchange domestic for foreign currency next period at the 1-period forward ($1/F_t^Q$). In other words, a bank that executes an FX swap his effectively engaging in the CIP arbitrage trade. A bank earns a riskless log return of $\ln(Q_t I_t / F_t^Q) - \ln(I_t^*) = q_t + i_t - f_t^q - i_t^* = x_t^{cip}$ when executing an FX swap. A bank executing a FX swap is effectively borrowing on synthetic basis and lending on a cash basis in domestic currency.

Conversely, in a "reverse FX swap," a bank exchanges domestic for foreign currency at today's spot rate ($1/Q_t$) and agrees to exchange foreign for domestic currency next period at the 1-period forward rate agreed to today (F_t^Q). A bank executing a reverse FX swap is effectively borrowing on cash basis and lending on a synthetic basis in domestic currency and, thus, earns a riskless log return of $-x_t^{cip}$ in domestic currency.

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:

$$q_{t+1} - f_t^q = [(q_{t+1} - q_t) + (i_t^* - i_t)] + x_t^{cip} = rx_{t+1}^q + x_t^{cip}. \tag{39}$$

  which follows from using the expression for f_t^q in equation (38) 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 long-term 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, in a world where 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:

$$(r_{t+1}^{y^*} + f_t^q - q_t) - i_t = rx_{t+1}^{y^*} - x_t^{cip}, \tag{40}$$

  which follows from using equation (38) 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.[38]

[38]In practice, FX-hedged positions in foreign risky assets do not completely eliminate the exchange rate risk investors must bear because the size of the hedge cannot be made dependent on the foreign assets' return. Thus, in practice, the FX-hedged return includes an interaction between the local currency foreign asset return and the FX return. For simplicity, we omit this second-order term in our analysis.

- *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:

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

  which follows from using equation (38) and $rx_{t+1}^y \equiv r_{t+1}^y - i_t$. 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}. Using forwards to hedge FX risk in this way is effectively a way of converting foreign currency funding into domestic currency funding.

Investor types We assume half of all global bond investors are domiciled in the home country and half are domiciled in the foreign country. Both domestic and foreign bond investors have mean-variance preferences over one-period-ahead wealth and a risk tolerance of τ in domestic currency terms.[39] 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 $[rx_{t+1}^y, rx_{t+1}^{y^*} - x_t^{cip}, rx_{t+1}^q + x_t^{cip}]'$. Note that 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 non-risk-based balance sheet costs, from fully arbitraging away deviations from CIP. It is equivalent to assuming that bond investors cannot

[39] Thus, at time t, the risk tolerance of foreign bond investors is τ/Q_t in foreign currency terms, which corresponds to a risk tolerance of τ in domestic currency terms.

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:

$$\max_{d_{B,t}^{cip}} \left\{ x_t^{cip} d_{B,t}^{cip} - (\kappa/2)\, (d_{B,t}^{cip})^2 \right\}, \tag{42}$$

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:

$$d_{B,t}^{cip} = \kappa^{-1} x_t^{cip}. \tag{43}$$

These assumptions are purposely stark and serve to highlight the key mechanisms in this model extension. In particular, our results would be qualitatively unchanged if some bond investors could engage in the CIP arbitrage trade in limited size. Similarly, we are assuming here 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. We would obtain qualitatively similar results if we assumed that banks had finite risk-bearing capacity and could also make risky forward FX investments.

Market equilibrium We need to clear four markets at time t: (i) the market for risky long-term domestic bonds, which are in net supply s_t^y; (ii) the market for risky long-term foreign bonds, which are in net supply s_t^{y*}; (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. 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 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 riskless 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. While not necessary, we can add exogenous shocks to the supply of the CIP arbitrage trade that banks must undertake:

$$s_{t+1}^{cip} = \phi_{s^{cip}} s_t^{cip} + \varepsilon_{s_{t+1}^{cip}}, \tag{44}$$

where $Var_t[\varepsilon_{s_{t+1}^{cip}}] = \sigma_{s^{cip}}^2 \geq 0$, $\phi_{s^{cip}} \in [0,1)$, and $\varepsilon_{s_{t+1}^{cip}}$ is orthogonal to the other five shocks.[40]

[40] If we allow for independent shifts in s_t^{cip} and s_t^q in this setting, we are implicitly assuming that the preferred

However, it is enough to 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.

In this setting, we can demonstrate the following results:

Proposition 5 ***Allowing for CIP deviations.*** *Consider the extended model where the banks are potentially balance-sheet constrained. We have the following results:*

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

$$
\begin{aligned}
E_t\left[rx_{t+1}^y\right] &= \tau^{-1}\left[V_y \times s_t^y + C_{y,y*} \times s_t^{y*} + C_{y,q} \times s_t^q\right] - x_t^{cip}/2, && \text{(45a)}\\
E_t\left[rx_{t+1}^{y*}\right] &= \tau^{-1}\left[C_{y,y*} \times s_t^y + V_y \times s_t^{y*} - C_{y,q} \times s_t^q\right] + x_t^{cip}/2, && \text{(45b)}\\
E_t\left[rx_{t+1}^q\right] &= \tau^{-1}\left[C_{y,q} \times (s_t^y - s_t^{y*}) + V_q \times s_t^q\right] - x_t^{cip}, && \text{(45c)}\\
x_t^{cip} &= \underbrace{\kappa \frac{V_y + C_{y,y*}}{2\left(V_y + C_{y,y*}\right) + \tau\kappa}}_{>0}\left[-\left(s_t^y - s_t^{y*}\right) + 2 \times s_t^{cip}\right]. && \text{(45d)}
\end{aligned}
$$

Eqs. (45c) and (45d) show that the three supply shocks s_t^y, s_t^{y*}, and s_t^{cip} 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.

First, consider the limiting case where banks balance-sheet costs vanish ($\kappa \to 0$). In this case, CIP holds—i.e., we have $x_t^{cip} \to 0$, 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, equilibrium 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 on an FX-hedged basis to take advantage of the elevated domestic term premium. Because banks are balance-sheet constrained, banks are only willing to accommodate investor demand for FX hedges if 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 three supply shocks (s_t^y, s_t^{y*}, and s_t^{cip}) push x_t^{cip} and $E_t\left[rx_{t+1}^q\right]$ in opposite directions. As a result, these supply shocks induce a positive correlation

habitat investors and other outside customers who drive these shocks are not willing to elastically substitute between spot and synthetic currency exposures. Indeed, if outside customers were infinitely price elastic in this regard, then outside customers would enforce CIP.

between x_t^{cip} and 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 x_t^{cip} is a highly informative signal about the underlying supply-and-demand shocks that drive UIP failures in our model (i.e., movements in $E_t\left[rx_{t+1}^q\right]$).[41]

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, κ. 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 κ, x_t^{cip} must decline to induce balance-sheet constrained banks to accommodate hedging demand from foreign investors.

Once we allow for CIP deviations, domestic investors acquire an *endogenous* comparative advantage at absorbing domestic bond supply shocks relative to foreign investors. Intuitively, while domestic investors earn an expected excess return of $E_t\left[rx_{t+1}^y\right]$ on long-term domestic bonds, foreign investors earn $E_t\left[rx_{t+1}^y\right] + x_t^{cip}$. Since the domestic bond supply shocks leads x_t^{cip} to decline in equilibrium, the hedging costs of foreign investors rise when they would most like to use FX forwards to hedge the FX risk from buying domestic bonds, thereby giving domestic investors an advantage in accommodating domestic bond supply shocks.

This endogenous comparative advantage means that increasing bank balance sheet costs, κ, raises the impact of a domestic bond supply shock on domestic term premia ($E_t\left[rx_{t+1}^y\right]$) and FX premia ($E_t\left[rx_{t+1}^q\right]$), and reduces the impact on foreign term premia ($E_t\left[rx_{t+1}^{y*}\right]$). Intuitively, foreign investors do less to help accommodate the shock, raising the 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 Section 3, we showed that we can match many empirical regularities about term premiums and exchange rates using a segmented-markets model in which the marginal investors in the global bond market are specialized bond investors. While this simple approach is appealing, it does not capture two significant real-world features of bond and foreign exchange markets. First, real-world markets feature a variety of different investor types—each facing a different set of constraints—opening the door to meaningful segmentation *within* the global bond market.

[41] Note that deviations from CIP also directly affect expected returns. For instance, since the cross-currency basis x_t^{cip} impacts the returns investors earn by buying foreign currency on a forward basis, the expected appreciation of foreign currency must offset the cross-currency basis in equilibrium—i.e., $E_t[rx_{t+1}^q] = \tau^{-1}[C_{y,q} \times (s_t^y - s_t^{y*}) + V_q \times s_t^q] - x_t^{cip}$. Similarly, since 50% of potential investors earn (pay) the CIP arbitrage spread x_t^{cip} when buying long-term domestic (foreign) bonds on an FX-hedged basis, in equilibrium the expected excess returns on long-term domestic (foreign) bonds must fall (rise) by $x_t^{cip}/2$ relative to our baseline model where $\kappa = 0$.

Second, real world bond and foreign exchange markets involve substantial trading flows between different investor types (Evans and Lyons [2002] and Froot and Ramadorai [2005]).

In this extension, we 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. Furthermore, unless market segmentation is extreme, bond supply shocks have a larger impact on exchange rates than in our baseline model.

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 τ 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, μ, 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 (2009, 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. And, we associate FX specialists with the global commercial banks who play an outsized role in the foreign exchange market, but, who, are not natural holders of long-term bonds in either currency.

In the Online Appendix, we solve for equilibrium in this extension by aggregating demand across investor types and imposing market clearing. We obtain the following results:

Proposition 6 ***Further segmenting the bond market.*** *Suppose $\rho < 1$, $\sigma_{s^y}^2 \geq 0$, $\sigma_{s^q}^2 \geq 0$. Suppose fraction μ of investors are specialists. We have the following results:*

(i.) ***Segmentation leads to endogenous trading flows.*** *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.*

(ii.) ***(a) Greater segmentation increases own-market price impact.*** *Formally, for any $a \in \{y, y^*, q\}$, $\partial^2 E_t[rx^a_{t+1}]/\partial s^a_t \partial\mu > 0$.* ***(b) Segmentation has a hump-shaped effect on cross-market price impact.*** *Formally, for any $a \in \{y, y^*, q\}$ and $a' \neq a$, $\left|\partial E_t[rx^a_{t+1}]/\partial s^{a'}_t\right|$ is hump-shaped function of μ with $\left|\partial E_t[rx^a_{t+1}]/\partial s^{a'}_t\right| > 0$ when $\mu = 0$ and $\partial E_t[rx^a_{t+1}]/\partial s^{a'}_t = 0$ 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 $rx^{s_t}_{t+1} = \mathbf{s}'_t \mathbf{rx}_{t+1}$ is increasing in μ: $\partial E_t[rx^{s_t}_{t+1}]/\partial\mu > 0$.*

(iii.) ***If asset supply is stochastic, greater segmentation increases market volatility.*** *Formally, for any arbitrary bond portfolio $\mathbf{p}_t \neq \mathbf{0}$ with returns $rx^{p_t}_{t+1} = \mathbf{p}'_t \mathbf{rx}_{t+1}$, we have $\partial Var_t[rx^{p_t}_{t+1}]/\partial\mu > 0$. (If asset supply is constant, volatility is independent of μ.)*

Increasing μ—i.e., further segmenting the global bond market—has two direct effects on the market equilibrium. First, as we increase μ, risk sharing becomes less efficient because fewer investors can absorb a given supply shock. For instance, the fraction of investors who can absorb a shock to domestic bond supply is $\mu\pi + (1-\mu)$, which is decreasing in μ. This gives rise to an "inefficient risk-sharing" effect. Second, as we increase μ, we replace global bond investors whose demands take the correlations between the three assets into account with specialist investors who, taken as a group, behave as if the three returns are uncorrelated. This gives rise to a "width of the pipe" effect: price impact is only transmitted across markets to the extent there are investors—"the pipe"—whose demands are impacted by shocks to other markets. Finally, there is a third indirect effect of increasing segmentation. To the extent that greater segmentation directly raises the price impact of supply shocks, greater segmentation amplifies return volatility, further increasing price impact. This is an "endogenous risk effect."

As we raise μ, these three effects always increase the impact of a supply shock in market a on expected returns in that market: $\partial^2 E_t[rx^a_{t+1}]/\partial s^a_t \partial\mu > 0$ 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, $\partial E_t[rx^q_{t+1}]/\partial s^y_t$, as a function of μ. When there are only global rates investors ($\mu = 0$), a shock to domestic bond supply raises expected returns on the FX trade: $\partial E_t[rx^q_{t+1}]/\partial s^y_t > 0$. This is the key result from our baseline model. By contrast, $\partial E_t[rx^q_{t+1}]/\partial s^y_t = 0$ when $\mu = 1$ and there are no global rates investors—i.e., when markets are completely segmented. In between, however, μ 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 $\partial E_t[rx^q_{t+1}]/\partial s^y_t$ to rise with μ and dominates when μ is near 0, and the width of the pipe effect, which typically leads $\partial E_t[rx^q_{t+1}]/\partial s^y_t$ to fall with μ and dominates when μ is near 1. Furthermore, the endogenous risk effect amplifies the net of these two effects, so the hump-shaped pattern is more pronounced when there is more supply risk.

These results are illustrated in Figure 3.[42] Panel A of Figure 3 plots the impact of a domestic bond supply shock on expected returns as a function of μ. The plot shows that, while $\partial E_t[rx^y_{t+1}]/\partial s^y_t$ is always increasing in μ, segmentation has a hump-shaped effect on $\partial E_t[rx^q_{t+1}]/\partial s^y_t$. Unless μ is near 1 and the global rates 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 μ has fallen over time. In other words, relative to earlier periods where markets were highly segmented ($\mu \approx 1$), the global rates market has gradually become more integrated, raising $\partial E_t[rx^q_{t+1}]/\partial s^y_t$ (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 μ. When $\mu \in (0, 1)$, markets are partially segmented, meaning that global bond investors and the three specialist types disagree on the appropriate compensation for bearing factor risk exposure. 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. Foreign exchange 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 flows are tied to supply-and-demand shocks for long-term domestic or foreign 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 foreign exchange risk. In our second extension, we add bond investors who cannot hedge foreign exchange 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 rates investors, who can separately manage their exposures to foreign currency and the foreign yield-curve trades,

[42] To draw all figures in the paper, we assume there is some FX-specific fundamental risk: we assume $\lim_{T\to\infty} E_t[q_{t+T}] = q^\infty_t$ follows a random walk $q^\infty_{t+1} = q^\infty_t + \varepsilon_{q^\infty,t+1}$ with $Var_t[\varepsilon_{q^\infty,t+1}] = \sigma^2_{q^\infty} > 0$, implying $q_t = q^\infty_t + \sum_{j=0}^{\infty} E_t[(i^*_{t+j} - i_{t+j}) - rx^q_{t+j+1}]$. If $\sigma^2_{q^\infty} = 0$, 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. Thus, if we instead assumed $\sigma^2_{q^\infty} = 0$ in Figure 3, global bond investors would take very large long-short positions as μ approached 1 since they would face no fundamental risk and would only be exposed to supply risk. Furthermore, while cross-market impact would still be hump-shaped when $\sigma^2_{s^q}, \sigma^2_{s^y} > 0$, instead of the smooth plots in Figure 3, there would be a sudden decline in cross-market impact once μ became very close to 1. Indeed, in the limit where $\sigma^2_{q^\infty} = \sigma^2_{s^q} = \sigma^2_{s^y} = 0$, cross-market impact would increase in μ for all $\mu \in (0, 1)$ and then discontinuosly vanish at $\mu = 1$.

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 τ 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 $rx^{y^*}_{t+1} + rx^{q}_{t+1}$ 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 $rx^{y}_{t+1} - rx^{q}_{t+1}$ 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 rates 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 7 ***Adding unhedged bond investors.*** *Suppose $\rho < 1$, $\sigma^2_{s^y} \geq 0$, and $\sigma^2_{s^q} \geq 0$. Suppose fraction η of bond investors cannot hedge FX risk. We have the following results:*

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

(ii.) Increasing the fraction of unhedged investors η: (a) increases own-market price impact: $\partial^2 E_t\left[rx^a_{t+1}\right]/\partial s^a_t \partial\eta > 0$ for all $a \in \{y, y^*, q\}$; (b) reduces the impact of domestic bond supply shocks on long-term foreign yields and vice-versa: $\partial^2 E_t\left[rx^{y*}_{t+1}\right]/\partial s^y_t \partial\eta < 0$ and $\partial^2 E_t\left[rx^{y}_{t+1}\right]/\partial s^{y*}_t \partial\eta < 0$; (c) increases the impact of bond supply shocks on exchange rates: $\partial^2 E_t\left[rx^{q}_{t+1}\right]/\partial s^y_t \partial\eta > 0$ and $\partial^2 E_t\left[rx^{q}_{t+1}\right]/\partial s^{y*}_t \partial\eta < 0$; and (d) raises the expected returns on the bond market portfolio $rx^{s_t}_{t+1} = \mathbf{s}'_t \mathbf{rx}_{t+1}$: $\partial E_t[rx^{s_t}_{t+1}]/\partial\eta > 0$ for any $\mathbf{s}_t \neq \mathbf{0}$.

(iii.) ***If asset supply is stochastic, increasing the fraction of unhedged bond investors raises market volatility.*** *If asset supply is stochastic, for any arbitrary portfolio $\mathbf{p}_t \neq \mathbf{0}$ with returns $rx^{p_t}_{t+1} = \mathbf{p}'_t \mathbf{rx}_{t+1}$, we have $\partial Var_t[rx^{p_t}_{t+1}]/\partial\eta > 0$.*

Figure 3 shows how a domestic bond supply shock impacts expected returns of as a function of the fraction of unhedged investors η. In our baseline model where $\eta = 0$, an increase in domestic bond supply s_t^y raises the expected returns on all three carry trades. As η rises, the impact on domestic bond returns rises. Own-market price impact rises because we are replacing global rates 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 η 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 η: 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 η: otherwise unhedged foreign investors' demand for foreign bonds will exceed the (unchanged) net supply of foreign bonds. Finally, as η 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 η 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 η 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 η. 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 rates 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 intuition about how QE policies may impact exchange rates rates. Specifically, 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—would 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 rates 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 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. Thus, if the global rates market is partially segmented from the broader global capital market, shocks to supply of other rate-sensitive assets—such as long-term domestic and foreign bonds—will 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.

Shocks to rate-insensitive assets will only impact exchange rates if investors cannot hedge their FX exposures. For instance, we can add domestic and foreign stocks to the model, assuming that equity premia are only driven by equity supply-and-demand shocks that are independent of those driving bond markets. Under this strong assumption, excess returns on domestic and foreign equities are naturally uncorrelated with those on foreign exchange.

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 equity investors to purchase domestic equities, but they will do so on a fully FX-hedged basis. Thus, the FX exposure of equity investors and global bond investors will be unchanged.

However, if some equity investors cannot hedge FX risk or there are CIP violations, then equity supply shocks will also impact FX rates even though equities are not inherently interest-rate sensitive. In these cases, equity investors will not fully FX-hedge their investments, meaning that equity supply shocks change the FX exposure of equity investors and global bond investors. Thus, when FX hedging is limited, shocks to interest-rate-insensitive assets can impact exchange rates and deviations from CIP, consistent with recent empirical findings (Hau and Rey [2005], Hau, Massa, and Peress [2009], Lilley, Maggiori, Neiman, and Schreger [2019], Pandolphini and Williams [2019]).

6 Conclusion

We have developed a quantity-driven model where 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 means that global bond and foreign exchange markets are potentially disconnected from aggregate consumption dynamics.

This simple model captures many features of the data, including (i) the correlations amongst the realized excess returns on foreign currency and those on foreign and domestic long-term bonds, (ii) the relationship between the foreign exchange risk premium and the risk premiums on foreign and domestic bonds, (iii) the effects of quantitative easing policies on exchange rates, and (iv) the fact that currency trades are potentially more profitable when implemented using short-term bonds than using long-term bonds. In addition, our baseline model provides a natural and unified account linking the Fama (1984) result on the predictability of foreign exchange returns with the Campbell-Shiller (1989) result on the predictability of long-term bond returns. While our baseline model captures many empirical regularities, shocks to the supply of long-term bonds do not generate trading flows in the foreign exchange market. We extend the model by introducing investors who cannot flexibly trade bonds of any maturity in both currencies, thus further segmenting the global bond market. In the presence of these constrained investors, shocks to the supply of long-term bonds lead to endogenous trading flows in currency markets that are associated with movements in the exchange rate. In addition, the presence of constrained investors typically amplifies the impact of bond supply shocks on exchange rates. 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, rather than changes in the short-term rates, to provide monetary accommodation. Indeed, our analysis leaves open the interesting possibility that when other conventional channels of transmission are compromised by very 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, it would follow that the arguments for monetary-policy coordination made by Rajan (2016) gather more force near the ZLB.[43] 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.

[43] Rajan (2016) writes: "....the unconventional 'quantitative easing' policy of buying assets such as long term bonds from domestic players may certainly lower long rates but may not have an effect on domestic investment if aggregate capacity utilization is low ... And if certain domestic institutional investors such as pension funds and insurance companies need long term bonds to meet their future claims, they may respond by buying such bonds in less distorted markets abroad. Such a search for yield will depreciate the exchange rate. The primary effect of this policy on domestic demand may be through the 'demand switching' effects of a lower exchange rate rather than through a demand creating channel. Of course, if all countries engage in demand switching policies, we could have a race to the bottom, with no one any better off."

A Additional results

A.1 Allowing for asymmetries between the two countries

This Appendix discusses how the results of our baseline model in Section 3 generalize if we allow the two countries to have different short rate and bond supply processes.

First, since the stable equilibrium is continuous in the model's underlying parameters, Proposition 2 implies that $C_{y,q} > 0$ whenever $\rho < 1$ and the short rates and bond supply follow sufficiently symmetric processes. For example, while $Cov_t[rx^y_{t+1}, rx^q_{t+1}] \neq -Cov_t[rx^{y*}_{t+1}, rx^q_{t+1}]$, we still have $Cov_t[rx^y_{t+1}, rx^q_{t+1}] > 0$ and $Cov_t[rx^{y*}_{t+1}, rx^q_{t+1}] < 0$ if there are moderate asymmetries between the domestic and foreign short rate and bond supply processes—e.g., there can be moderate differences in either the volatilities or persistences. Furthermore, $C_{y,y^*} > 0$ whenever $\rho > 0$, the short rates and bond supply follow sufficiently symmetric processes, and when FX supply risk is sufficiently small relative to ρ.

However, things grow more complicated if we allow for highly asymmetric short rate and bond supply processes. For instance, with highly asymmetric short rate processes, the sign of $C_{y,q}$ is ambiguous and the sign of $C_{y*,q}$ need not opposite that of $C_{y,q}$. For instance, suppose that $\sigma^2_{i^*} \equiv Var_t[\varepsilon_{i^*_{t+1}}] \neq Var_t[\varepsilon_{i_{t+1}}] \equiv \sigma^2_i$, but the two short rates share the same persistence ϕ_i. Then, focusing on the limit where there is no supply risk for simplicity, we have

$$C_{y,y^*} = \left(\frac{\delta}{1-\delta\phi_i}\right)^2 \rho\sigma_i\sigma_{i^*}, \tag{46a}$$

$$C_{y,q} = \frac{1}{1-\phi_i}\frac{\delta}{1-\delta\phi_i}\sigma^2_i\left(1-\rho\frac{\sigma_{i^*}}{\sigma_i}\right) \tag{46b}$$

$$C_{y^*,q} = -\frac{1}{1-\phi_i}\frac{\delta}{1-\delta\phi_i}\sigma^2_{i^*}\left(1-\rho\frac{\sigma_i}{\sigma_{i^*}}\right). \tag{46c}$$

While we still have $C_{y,y^*} > 0$ so long as $\rho > 0$, the behavior of $C_{y,q}$ and $C_{y^*,q}$ is more complicated. Noting that $\rho\sigma_{i^*}/\sigma_i$ ($\rho\sigma_i/\sigma_{i^*}$) is the coefficient from a regression of i^*_t on i_t (i_t on i^*_t), there are now three possible case:[44]

1. If $1 > \max\{\rho\sigma_{i^*}/\sigma_i, \rho\sigma_i/\sigma_{i^*}\}$—i.e., if the short rates are sufficiently symmetric, $C_{y,q} > 0$ and $C_{y^*,q} < 0$.

2. If $\rho\sigma_{i^*}/\sigma_i > 1 > \rho\sigma_i/\sigma_{i^*}$—i.e., if foreign short rates move more than one-for-one with domestic short rates, then $C_{y,q} < 0$ and $C_{y^*,q} < 0$.

3. If $\rho\sigma_i/\sigma_{i^*} > 1 > \rho\sigma_{i^*}/\sigma_i$—i.e., if domestic short rates move more than one-for-one with foreign short rates, $C_{y,q} > 0$ and $C_{y^*,q} > 0$.

In other words, in the event of a positive shock to the supply of long-term dollar bonds, foreign currencies with $\rho\sigma_{i^*}/\sigma_i < 1$ would be expected to *depreciate* against the dollar on impact and then appreciate going forward: this is the case emphasized in the main text. By contrast, foreign currencies with $\rho\sigma_{i^*}/\sigma_i > 1$ would be expected to *appreciate* versus the dollar on impact and then depreciate going forward. To see the intuition, suppose that $\rho\sigma_{i^*}/\sigma_i > 1 > \rho\sigma_i/\sigma_{i^*}$, so foreign short rates move more than one-for-one with domestic short rates. Here an increase in the supply of long-term domestic bonds leads to a larger increase in the price of foreign short rate

[44] However, since $\min\{\rho\sigma_{i^*}/\sigma_i, \rho\sigma_i/\sigma_{i^*}\} < 1$, we can never have $C_{y,q} < 0$ and $C_{y^*,q} > 0$.

risk than in the price of domestic foreign short rate risk. Since foreign exchange has a positive exposure to domestic short rates and a negative—and opposite—exposure to foreign short rates, the increase in domestic bond supply actually reduces the expected future return on foreign exchange, leading foreign currency to appreciate today. And, since an increase in foreign bond supply also has a larger impact on the price of foreign short rate risk, such a shock also leads foreign currency to appreciate.

A.2 Contrast with frictionless asset-pricing models

In this Appendix, we contrast the results from our baseline model in Section 3 with those implied by frictionless, consumption-based asset pricing models. Consider a frictionless asset-pricing model featuring complete international financial markets, but imperfect risk sharing between the home and foreign countries. Since financial markets are complete, the stochastic discount factor is unique, implying:

$$M_{t+1}^{*} = M_{t+1}\left(Q_{t+1}/Q_{t}\right). \tag{47}$$

where Q_t is the foreign exchange rate, M_{t+1} is stochastic discount factor (SDF) that price all returns in domestic currency, and M_{t+1}^{*} is discount factor pricing all returns in formal currency (Backus, Foresi, Telmer [2001]).

Taking logs we find:

$$q_{t+1} - q_t = m_{t+1}^{*} - m_{t+1}. \tag{48}$$

Thus, frictionless theories imply that foreign currency appreciates in bad times for foreign agents where m_{t+1}^{*} is high and depreciates in bad times for domestic agents when m_{t+1} is high. These exchange rate dynamics make domestic assets risky for foreign agents and vice versa, rationalizing imperfect international risk sharing even with complete financial markets.

As shown in Table 6, consumption-based theories typically imply that foreign interest rates decline in bad times for foreign agents, so standard uncovered-interest-rate-parity (UIP) logic pushes foreign currency toward depreciating in bad times for foreign agents. However, by construction, this UIP effect needs to more than fully offset in consumption-based models by either a temporary appreciation of foreign currency (i.e., by news that the expected returns on foreign currency will be lower going forward, perhaps, because $E_t\left[rx_{t+1}^{q}\right]$ is increasing in $(i_t^{*} - i_t)$) or by a permanent appreciation (i.e., by an innovation to a random walk component of the exchange rate).[45] Thus, many leading consumption-based models imply

$$Cov_t\left[\Delta q_{t+1}, \Delta\left(i_{t+1}^{*} - i_{t+1}\right)\right] = Cov_t\left[rx_{t+1}^{q}, i_{t+1}^{*} - i_{t+1}\right] < 0. \tag{49}$$

By contrast, in our theory as in the data, we have $Cov_t\left[\Delta q_{t+1}, \Delta\left(i_{t+1}^{*} - i_{t+1}\right)\right] > 0$.

[45] We have $q_{t+1} = -\sum_{j=1}^{T}(m_{t+1+j}^{*} - m_{t+1+j}) + q_{t+T}$. Letting $E_{t+1}\left[q_{t+\infty}\right] \equiv \lim_{T\to\infty} E_{t+1}\left[q_{t+T}\right]$ and taking expectations and the limit as $T \to \infty$, we obtain $q_{t+1} = -\sum_{j=1}^{\infty} E_{t+1}[m_{t+1+j}^{*} - m_{t+1+j}] + E_{t+1}\left[q_{t+\infty}\right] = \sum_{j=0}^{\infty} E_{t+1}[i_{t+1+j}^{*} - i_{t+1+j} - rx_{t+2+j}^{q}] + E_{t+1}\left[q_{t+\infty}\right]$. Since

$$(E_{t+1} - E_t)\, q_{t+1} = \overbrace{\textstyle\sum_{j=0}^{\infty}(E_{t+1} - E_t)\left[i_{t+1+j}^{*} - i_{t+1+j}\right]}^{\mathcal{N}_{t+1}^{i^{*}-i}} - \overbrace{\textstyle\sum_{j=0}^{\infty}(E_{t+1} - E_t)\left[rx_{t+2+j}^{q}\right]}^{\mathcal{N}_{t+1}^{rx^{q}}} + \overbrace{(E_{t+1} - E_t)\left[q_{t+\infty}\right]}^{\mathcal{N}_{t}^{q\infty}}$$

unexpected movements in exchange rates must either reflect news about the future interest rate differentials ($\mathcal{N}_{t+1}^{i^{*}-i}$), news about future excess returns on foreign exchange ($\mathcal{N}_{t+1}^{rx^{q}}$), or permanent news about the long-run level of foreign currency ($\mathcal{N}_{t}^{q\infty}$).

Assuming that both the foreign and domestic SDFs are log-normally distributed, we have

$$E_t\left[rx^q_{t+1}\right] = E_t\left[q_{t+1} - q_t + (i^*_t - i_t)\right] = \frac{1}{2}\left(\sigma^2_t[m_{t+1}] - \sigma^2_t\left[m^*_{t+1}\right]\right), \tag{50}$$

which follows from the facts that $q_{t+1} - q_t = m^*_{t+1} - m_{t+1}$, $i_t = -E_t[m_{t+1}] - \sigma^2_t[m_{t+1}]/2$, and $i^*_t = -E_t[m^*_{t+1}] - \sigma^2_t[m^*_{t+1}]/2$. Thus, the expected excess return on foreign currency is one half the difference between the conditional variances of the domestic and foreign log SDFs. In other words, foreign currency risk premium will be high when domestic agents are more risk averse than foreign agents or when domestic agents are exposed to greater macroeconomic risk.

Similarly, assuming the local-currency excess returns on long-term bonds are jointly log-normal, we have:

$$E_t[rx^y_{t+1}] + \frac{1}{2}\sigma^2_t[rx^y_{t+1}] = -Corr_t[rx^y_{t+1}, m_{t+1}]\sigma_t[rx^y_{t+1}]\sigma_t[m_{t+1}], \tag{51a}$$

$$E_t[rx^{y^*}_{t+1}] + \frac{1}{2}\sigma^2_t[rx^{y^*}_{t+1}] = -Corr_t[rx^{y^*}_{t+1}, m^*_{t+1}]\sigma_t[rx^{y^*}_{t+1}]\sigma_t\left[m^*_{t+1}\right]. \tag{51b}$$

Consumption-based models almost always imply that $Corr_t[rx^y_{t+1}, m_{t+1}] > 0$ and $Corr_t[rx^{y^*}_{t+1}, m^*_{t+1}] > 0$—i.e., long-term domestic (foreign) bonds are an attractive hedge for domestic (foreign) investors. The idea is that domestic interest rates typically decline when the domestic agents' marginal value of financial wealth is unexpectedly high (e.g., because the SDF is persistent or because the volatility of the SDF rises in bad times), leading the prices of long-term domestic bonds to rise in these states of the world.

In our model, $E_t\left[rx^q_{t+1}\right]$ is negatively related to $E_t[rx^{y^*}_{t+1} - rx^y_{t+1}]$—i.e., the expected excess returns on foreign exchange are decreasing in the foreign-minus-domestic term premium. What do leading consumption-based model imply? In modern consumption-based models, the main reason expected returns fluctuate over time is because the conditional volatilities of SDFs ($\sigma_t[m_{t+1}]$ and $\sigma_t[m^*_{t+1}]$) vary over time—e.g., due to time-varying risk aversion as in habit formation models (Campbell and Cochrane [1999]), time-varying consumption volatility as in long-run risks models (Bansal and Yaron [2004]), or a time-varying probability of a rare economic disaster (Gabaix [2012] and Wachter [2013]). Thus, since $Corr_t[rx^y_{t+1}, m_{t+1}] > 0$, an increase in $\sigma_t[m_{t+1}]$ raises $E_t[rx^q_{t+1}]$, but reduces $E_t[rx^y_{t+1}]$—i.e., $Corr\left(E_t[rx^q_{t+1}], E_t[rx^y_{t+1}]\right) < 0$. By contrast, in our model, $E_t[rx^q_{t+1}]$ tends to be high at the same time that $E_t[rx^y_{t+1}]$ is also high—i.e., $Corr\left(E_t[rx^q_{t+1}], E_t[rx^y_{t+1}]\right) > 0$. Symmetrically, since $Corr_t[rx^{y^*}_{t+1}, m^*_{t+1}] > 0$, an increase in $\sigma_t[m^*_{t+1}]$ reduces $E_t[rx^q_{t+1}]$ and also reduces $E_t[rx^{y^*}_{t+1}]$—i.e., $Corr(E_t[rx^q_{t+1}], E_t[rx^{y^*}_{t+1}]) > 0$. By contrast, in our model, we have $Corr(E_t[rx^q_{t+1}], E_t[rx^{y^*}_{t+1}]) < 0$.

This crucial difference stems from two differences between our theory and standard frictionless theories. First, we assume that the global rates market is partially segmented from the broader capital markets as well as from ultimate consumption. As a result, long-term bonds are potentially risky for the specialized bond investors who are the relevant marginal holders of long-term bonds. Second, in consumption-based models, the realized returns on foreign currency are positively correlated with those on long-term foreign bonds and negatively correlated with those on domestic bonds. By contrast, in our theory as in the data, the realized returns on foreign currency are negatively correlated with those on long-term foreign bonds and positively correlated with those on domestic bonds.

To see this juxtaposition starkly, suppose that $\sigma^2_t[rx^y_{t+1}] = \sigma^2_t[rx^{y^*}_{t+1}] = \sigma^2_y$ and that $Corr_t[rx^y_{t+1}, m_{t+1}] =$

$Corr_t[rx^{y^*}_{t+1}, m^*_{t+1}] = \varrho_{y,m} > 0$ are constant over time, so

$$E_t[rx^y_{t+1}] + \frac{1}{2}\sigma^2_y = -\varrho_{y,m}\sigma_y\sigma_t[m_{t+1}], \tag{52a}$$

$$E_t[rx^{y^*}_{t+1}] + \frac{1}{2}\sigma^2_y = -\varrho_{y,m}\sigma_y\sigma_t[m^*_{t+1}]. \tag{52b}$$

Thus, all time-series variation in foreign and domestic bond risk premia is driven by time-variation in the conditional volatility of the domestic and foreign SDFs. However, this implies that

$$E_t[rx^{y*}_{t+1} - rx^y_{t+1}] = \varrho_{y,m}\sigma_y\left(\sigma_t[m_{t+1}] - \sigma_t[m^*_{t+1}]\right). \tag{53}$$

Using Eq. (50), we find that:

$$E_t\left[rx^q_{t+1}\right] = \overbrace{\left[\frac{\sigma_t[m_{t+1}] + \sigma_t[m^*_{t+1}]}{2\varrho_{y,m}\sigma_y}\right]}^{>0} \times E_t[rx^{y*}_{t+1} - rx^y_{t+1}]. \tag{54}$$

Thus, most consumption-based theories predict a positive relationship between FX risk premia and the difference between foreign and domestic term premia. By contrast, as emphasized in Section 3, our theory implies a negative relationship between FX risk premia and the difference between foreign and domestic bond risk premia.

Turning to the expected return to the long-term FX trade, consumption-based models in this class imply that the expected returns on the long-term carry trade are greater in magnitude than those on the short-term FX trade:

$$E_t[rx^q_{t+1} + (rx^{y^*}_{t+1} - rx^y_{t+1})] = \overbrace{\left(1 + \frac{\sigma_t[m_{t+1}] + \sigma_t\left[m^*_{t+1}\right]}{2\varrho_{y,m}\sigma_y}\right)}^{>1} \times E_t\left[rx^q_{t+1}\right]. \tag{55}$$

By contrast, our model is consistent with the evidence in that the return on the long-term FX trade are smaller than those on the standard, short-term FX trade.

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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.

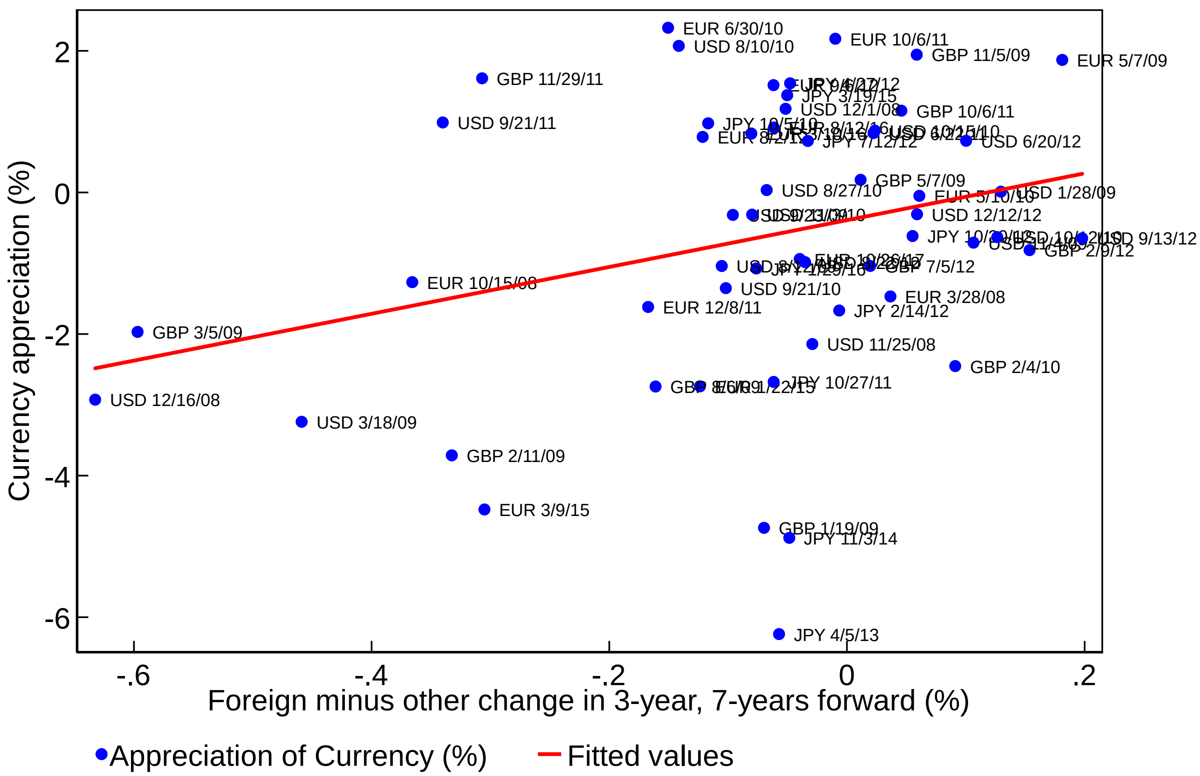
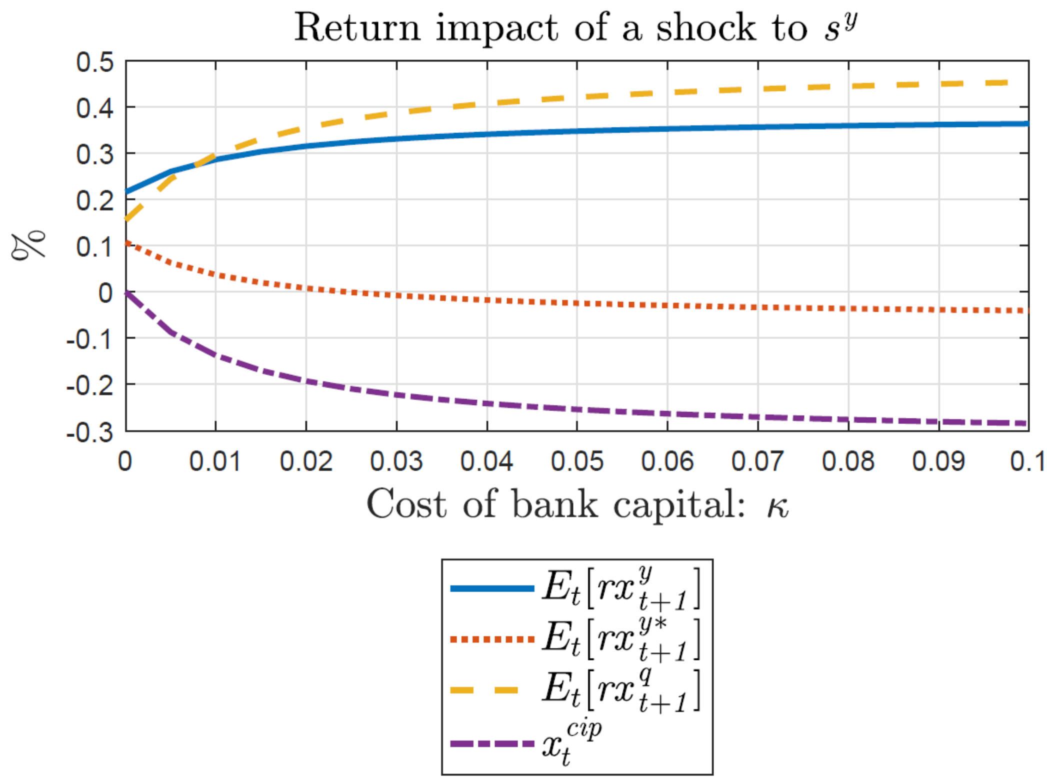


Figure 2. Allowing for deviations from covered-interest-rate parity (CIP). This figure illustrates the model allowing for CIP deviations from Section 4. The figure shows the impact of a shock to domestic bond supply on expected returns and investor holdings as a function of banks' costs of capital, κ. 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 σ_{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

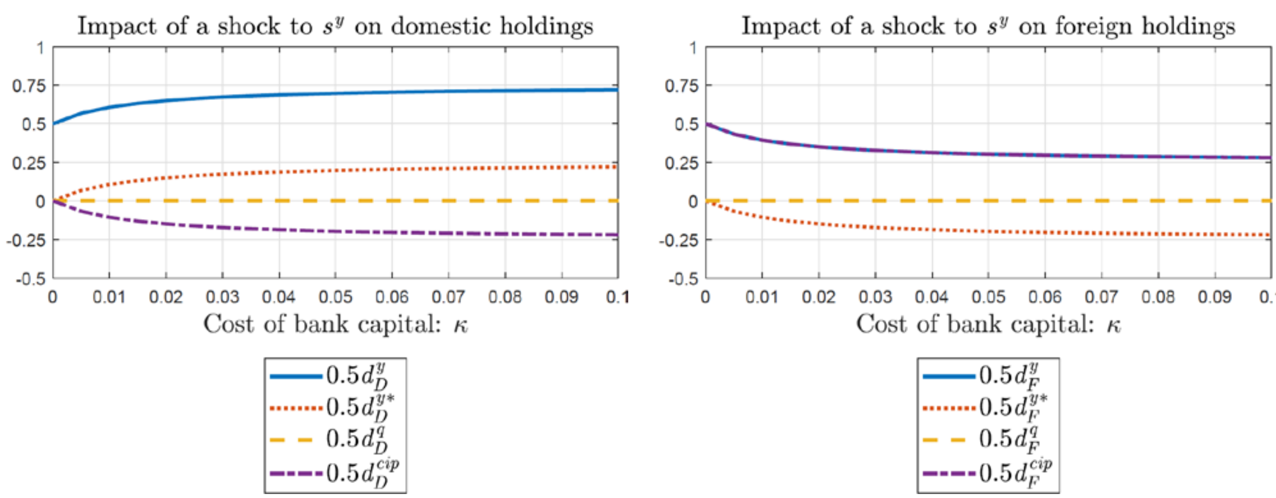
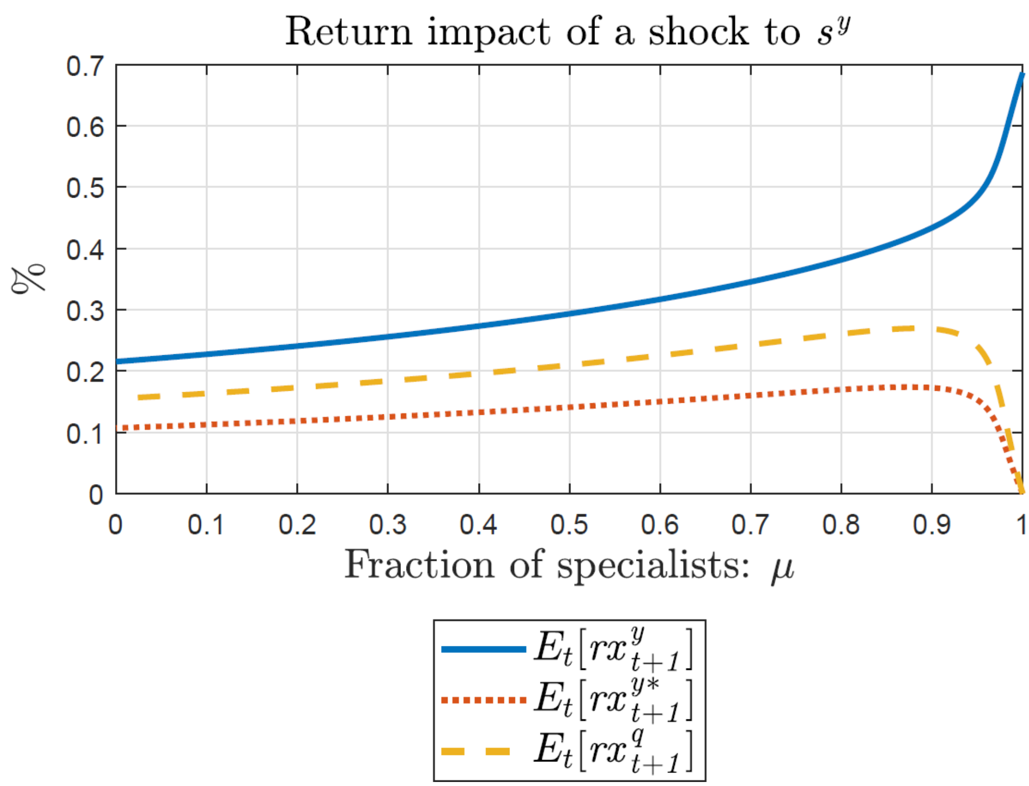


Figure 3. Further segmenting the global bond markets. This figure illustrates the model with further segmentation from Section 5.1. The figure shows the impact of a shock to domestic bond supply on expected returns and investor holdings as a function of the fraction of specialists, μ. The figure assumes $\pi = 1/3$, 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 σ_{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

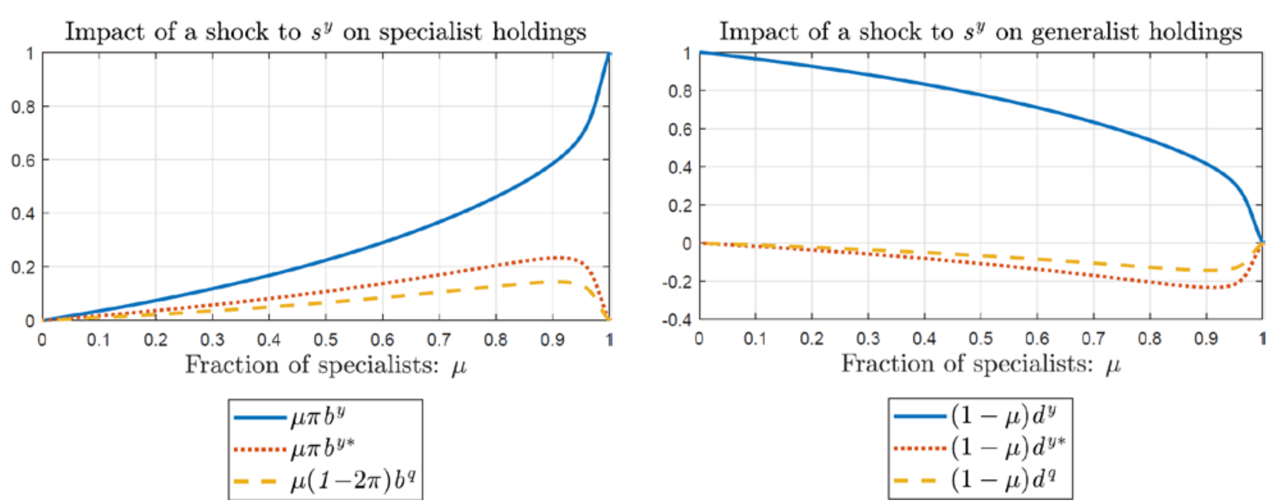
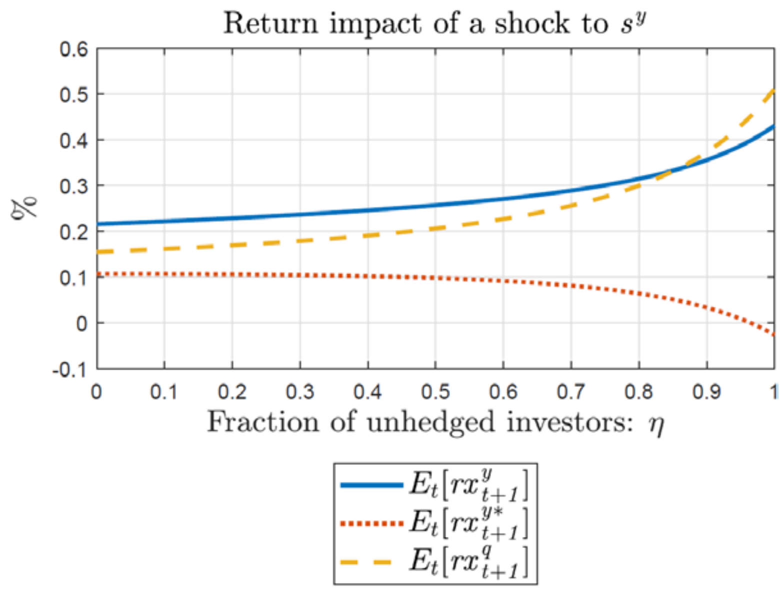


Figure 4. Unhedged bond investors. This figure illustrates the model with unhedged bond investors from Subsection 5.2. The figure shows the impact of a shock to domestic bond supply on expected returns and investor holdings as a function of the fraction of unhedged investors, η. We chose the other model 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 σ_{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

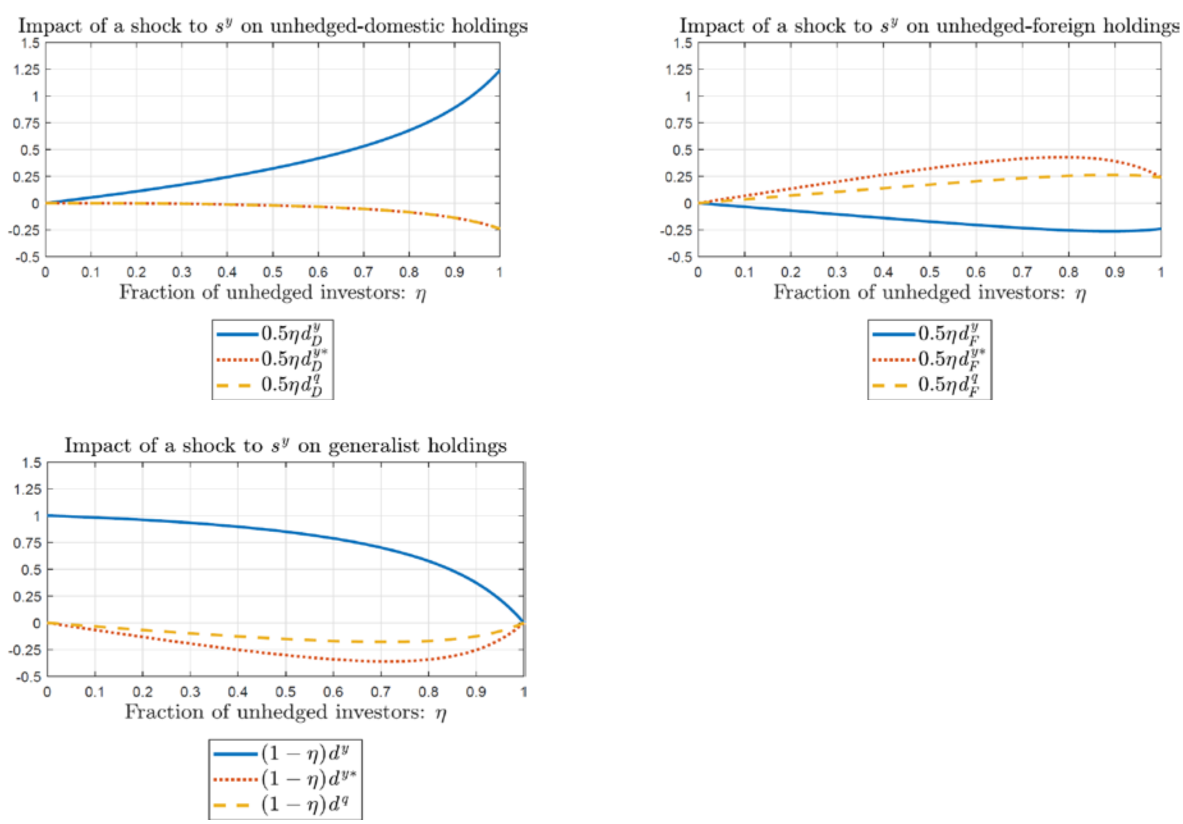


Table 1. Contemporaneous relationship between movements in foreign exchange, short-term interest rates, and long-term interest rates. This table presents monthly panel regressions of the form:

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

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***	3.51**			2.39	0.80		
	(1.63)	(1.69)			(1.54)	(1.64)		
$\Delta_h(y^*_{c,t} - y_t)$		4.37***				7.37***		
		(1.20)				(1.71)		
$\Delta_h i^*_{c,t}$			7.00***	5.86***			5.60***	2.45
			(1.32)	(1.34)			(1.37)	(1.90)
$\Delta_h i_t$			-3.87***	-2.50**			-1.84	-0.01
			(1.18)	(1.13)			(1.17)	(1.27)
$\Delta_h y^*_{c,t}$				5.09***				11.51***
				(1.48)				(2.26)
$\Delta_h y_t$				-4.83***				-7.44***
				(1.07)				(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***	4.72***			2.39	2.63		
	(1.63)	(1.56)			(1.54)	(1.51)		
$\Delta_h(f^*_{c,t} - f_t)$		2.99***				4.01***		
		(0.85)				(1.33)		
$\Delta_h i^*_{c,t}$			7.00***	7.02***			5.60***	5.33***
			(1.32)	(1.21)			(1.37)	(1.37)
$\Delta_h i_t$			-3.87***	-3.89***			-1.84	-1.62
			(1.18)	(1.11)			(1.17)	(1.16)
$\Delta_h f^*_{c,t}$				3.33***				7.10***
				(1.15)				(1.45)
$\Delta_h f_t$				-3.04***				-3.77**
				(0.76)				(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:

$$rx^{y*}_{c,t\to t+h} - rx^{y}_{c,t\to t+h} = A_c + B\times(i^*_{c,t} - i_t) + D\times(f^*_{c,t} - f_t) + \varepsilon_{c,t\to t+h},$$

and

$$rx^{y*}_{c,t\to t+h} - rx^{y}_{c,t\to t+h} = A_c + B_1\times i^*_{c,t} + B_2\times i_t + D_1\times f^*_{c,t} + D_2\times f_t + \varepsilon_{c,t\to t+h}.$$

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. $rx^{y*}_{c,t\to t+h} - rx^{y}_{c,t\to t+h}$ 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	-0.28**			-0.42	-0.53		
	(0.14)	(0.14)			(0.41)	(0.45)		
$f^*_{c,t} - f_t$		1.68***				4.16***		
		(0.31)				(0.45)		
$i^*_{c,t}$			-0.38**	-0.18			-1.06**	-0.58
			(0.15)	(0.16)			(0.42)	(0.42)
i_t			0.08	0.16			-0.02	0.17
			(0.16)	(0.15)			(0.44)	(0.44)
$f^*_{c,t}$				1.27***				3.02***
				(0.30)				(0.44)
f_t				-1.65***				-3.90***
				(0.33)				(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:

$$rx^{q}_{c,t\to t+h} = A_c + B\times(i^{*}_{c,t} - i_t) + D\times(f^{*}_{c,t} - f_t) + \varepsilon_{c,t\to t+h},$$

and

$$rx^{q}_{c,t\to t+h} = A_c + B_1\times i^{*}_{c,t} + B_2\times i_t + D_1\times f^{*}_{c,t} + D_2\times f_t + \varepsilon_{c,t\to t+h}.$$

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. $rx^{q}_{c,t\to t+h}$ 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	0.06			0.26	0.38		
	(0.36)	(0.34)			(1.47)	(1.43)		
$f^{*}_{c,t} - f_t$		-1.47***				-4.44***		
		(0.49)				(1.27)		
$i^{*}_{c,t}$			0.13	-0.24			1.05	0.11
			(0.43)	(0.49)			(1.73)	(1.73)
i_t			0.11	0.07			0.28	0.14
			(0.35)	(0.33)			(1.28)	(1.23)
$f^{*}_{c,t}$				-0.79				-2.32
				(0.57)				(1.64)
f_t				1.52***				4.21***
				(0.52)				(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**	10.46***		
	(3.26)	(1.90)		
$\Delta_4(f^*_{c,t+2} - f_{t+2})$		4.62***		
		(1.12)		
$\Delta_4 i^*_{c,t+2}$			7.36**	10.17***
			(3.22)	(2.00)
$\Delta_4 i_{t+2}$			-15.66**	-12.70**
			(7.35)	(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 with leading consumption-based models.

	Real short rates fall in recessions	Real short rates fall in "bad times" for bond investors	Real term premia can be positive: $E_t[rx^y_{t+1}]>0$	Shock to $i^*_{t+1}-i_{t+1}$ associated with foreign currency appreciation: $Cov_t[rx^q_{t+1}, i^*_{t+1}-i_{t+1}]>0$	FX trade loses (makes) money when foreign (domestic) yield-curve trade does: $Cov_t[rx^q_{t+1}, rx^{y*}_{t+1}-rx^y_{t+1}]<0$.	$E_t[rx^q_{t+1}]$ negatively related to $E_t[rx^{y*}_{t+1}-rx^y_{t+1}]$	Fama ('84) FX carry trade: $E_t[rx^q_{t+1}]$ is increasing in $(i^*_t-i_t)$	Campbell-Shiller ('91) yield curve carry trade: $E_t[rx^y_{t+1}]$ is increasing in (y_t-i_t)	Real yield curve steep when short rates low: (y_t-i_t) decreasing in i_t	Notes
Data	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Our model	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Textbook C-CAPM model: Power utility, homoskedastic growth shocks, positive autocorrelation of growth[i]	Yes	Yes	No	No	No	N/A	N/A	N/A	Yes	
Non-standard C-CAPM: Power utility, homoskedastic growth shocks, negative autocorrelation of growth[ii]	No	No	Yes	Yes	Yes	N/A	N/A	N/A	Yes	Reduces equity risk premium
Long-run risks: News about long-run growth, stochastic volatility, EZ-W utility, CRRA (γ) exceeds inverse-EIS (ψ^{-1}).[iii]	Yes	Yes	No	No	No	No	Yes	No/Yes	Yes/No	
Long-run risks: News about long-run growth, stochastic volatility, EZ-W utility, inverse-EIS (ψ^{-1}) exceeds CRRA (γ).[iv]	Yes	No	Yes	Yes	Yes	Yes	No	No/Yes	Yes/No	Reduces equity risk premium
Time-varying probability of rare consumption disasters[v]	Yes	Yes	No	No	No	No	Yes	No/Yes	Yes/No	
Habit formation: Short rate rises when surplus-consumption ratio rises[vi]	Yes	Yes	No	No	No	No	Yes	No/Yes	Yes/No	
Habit formation: Short rate falls when surplus-consumption ratio rises[vii]	No	No	Yes	Yes	Yes	Yes	No	No/Yes	Yes/No	

[i] See Campbell (1986), Campbell (2003), Campbell (2018).
[ii] See Campbell (1986), Campbell (2003), Campbell (2018).
[iii] See Campbell (2003), Bansal and Yaron (2004), Colacito and Croce (2011), Bansal and Shaliastovich (2013), Campbell (2018).
[iv] See Campbell (2003), Bansal and Yaron (2004), Colacito and Croce (2011), Bansal and Shaliastovich (2013), Campbell (2018).
[v] See Wachter (2013) and Campbell (2018).
[vi] See Campbell and Cochrane (1999), Wachter (2006), Verdelhan (2010), and Campbell (2018).
[vii] See Campbell and Cochrane (1999), Wachter (2006), Verdelhan (2010), and Campbell (2018).