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Scrambling for Dollars: International Liquidity, Banks and Exchange Rates

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Abstract

We develop a theory of exchange rate fluctuations arising from financial institutions' demand for dollar liquid assets. Financial flows are unpredictable and may leave banks "scrambling for dollars." Because of settlement frictions in interbank markets, a precautionary demand for dollar reserves emerges and gives rise to an endogenous convenience yield on the dollar. We show that an increase in the dollar funding risk leads to a rise in the convenience yield and an appreciation of the dollar, as banks scramble for dollars. We present empirical evidence on the relationship between exchange rate fluctuations for the G10 currencies and the quantity of dollar liquidity, which is consistent with the theory.

Keywords: Exchange rates, liquidity premia, monetary policy

JEL Classification: E44, F31, F41, G20

1 Introduction

The well-known "disconnect" in international finance holds that foreign exchange rates show little empirical relationship to the macro variables, such as interest rates and output (Obstfeld and Rogoff, 2000). More recent work contends that the source of the disconnect is in financial markets (Itskhoki and Mukhin, 2021a). Moreover, there has long been evidence of time-varying expected excess returns in foreign exchange markets, and furthermore, it appears that the US dollar is particularly special, as dollar assets offer lower average returns relative to the rest of the major currencies when measured on historical data (Gourinchas and Rey, 2007a). To account for the exchange rate disconnect and associated puzzles, the literature has turned to models with currency excess returns as the potential "missing link." The source or sources of these excess returns, however, remains an unsolved mystery.

In this paper, we develop a theory of exchange rate fluctuations arising from the liquidity demand by financial institutions within an imperfect interbank market. We build on two observations of the international financial system. First, US dollars are the dominant source of foreign-currency funding. According to the BIS locational banking statistics, in March 2021, the global banking and non-bank financial sector had cross-border dollar liabilities of over $11 trillion. Second, dollar funding may turn unstable. As documented, for example, in Acharya, Afonso, and Kovner (2017), banks are occasionally subject to large funding uncertainty or interbank market freezing that can leave them "scrambling for dollars." Narrative discussions attribute fluctuations in the US dollar exchange rate to such vicissitudes in the short-term international money markets. A contribution of our paper is to develop a framework to formally articulate this channel and provide empirical evidence consistent with it.

We construct a model in which financial institutions, which we refer to simply as "banks," hold assets and liabilities in two currencies. Banks face the risk of sudden outflows of liabilities. If a bank ends up short of liquid assets to settle those flows, it needs to find a counterparty, but there may be times when banks may lose confidence in one another and create frictions in the interbank market. As insurance against these outflows, banks maintain a buffer of liquid assets—especially dollar liquid assets, in line with the aforementioned observations on the international financial system. To the extent that funding risk and the frictions in the interbank markets vary over time, this changes the relative demand for currencies, resulting in movements in the exchange rate.

The theory uncovers how frictions in the settlement of international deposit flows emerge as a dollar liquidity premium. This dollar liquidity premium generates a time-varying wedge in the interest parity condition, or "convenience yield," which plays a

pivotal role in the determination of the exchange rate. Critically, the convenience yield is endogenous and depends on the quantity of outside money (liquid assets) and policy rates, as well as the matching frictions in the interbank market and the volatility of deposit flows in different currencies. Through this endogenous convenience yield, we link the nominal exchange rates and the dollar liquidity premium to the reserve position of banks in different currencies, funding risk, and confidence in the interbank market.

On the surface, the model resembles the seminal monetary exchange rate model of Lucas (1982).[1] In that model, two currencies earn a liquidity premium over bonds because certain goods must be bought with corresponding currencies. A money demand equation determines prices in both currencies, and relative prices determine the exchange rate. Our model shares Lucas's segmentation of transactions and exchange rate determination. However, in our model, the demand for reserves in either currency stems from the settlement demand by banks, giving rise to different predictions of how the exchange rate reacts to shocks and to policy. In particular, our model rationalizes why the dollar tends to appreciate in times of high volatility, therefore acting as a "safe haven". This phenomenon that has been challenging to reconcile with existing models of financial intermediaries (see, Maggiori, 2017).[2]

Many recent theories have focused primarily on risk premia or external financing premia to explain excess currency returns and exchange rate movements. Risk premium models explain excess dollar returns as stemming from how currencies other than the dollar have greater exposure to global pricing factors.[3] External financing premium models explain excess dollar returns as a funding advantage in dollar liabilities in the presence of limits to international arbitrage. We provide an alternative theory based on a liquidity premium. Our baseline model abstracts from risk premia and limits to international arbitrage to focus squarely on liquidity. At the center of the model is the idea that funding risk may leave banks scrambling for dollars.

We provide empirical evidence consistent with the theory by relating the banking sector's balance sheet data to the foreign currency price of US dollars. According to the theory, the financial sector increases its demand for liquid dollar assets relative to dollar funding—US government obligations, including Treasuries and reserves held at the Federal Reserve—when funding becomes more uncertain, and this in turn translates into an appreciation of the dollar. Our analysis shows that the dollar liquidity ratio, the

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[1]See also Svensson (1985) and Engel (1992a,b).

[2]Maggiori (2017) shows that in a global downturn, US households bear a larger share of the losses relative to the rest of the world. With home bias, this means that the dollar must experience a real depreciation in a global downturn.

[3]See, for example, Lustig, Roussanov, and Verdelhan (2011, 2014).

ratio of dollar liquid assets relative to dollar funding, does indeed positively correlate with the relative value of the dollar. Notably, this relationship is robust to controlling for the VIX index, a variable that captures a broad measure of uncertainty and has been shown to have significant explanatory power for exchange rates (Brunnermeier, Nagel, and Pedersen, 2008; Lilley, Maggiori, Neiman, and Schreger, 2019). The liquidity ratio is, of course, not an exogenous driver of exchange rates—neither in our model nor in the data. However, we show that a calibrated version of our model produces a positive relationship between the change in the liquidity ratio and the value of the dollar. Moreover, we demonstrate that, theoretically, funding risk drives this empirical correlation.

Literature Review

The expected excess return on foreign interest earning assets, or the deviation from "uncovered interest parity" (UIP), is important not just for understanding international pricing of interest-bearing assets, or the expected depreciation (or appreciation) of the currency, but also for understanding the level of the exchange rate. This point is brought to the fore by Obstfeld and Rogoff (2003), who show how the expected present value of current and future foreign exchange risk premiums affect the current exchange rate in a simple DSGE model. They refer to this present value as the "level risk premium."[4]

A better understanding of the role of ex ante excess returns can potentially help account for the empirical failure of exchange rate models (Meese and Rogoff, 1983; Obstfeld and Rogoff, 2000) and the excess volatility of exchange rates (Frankel and Meese, 1987; Backus and Smith, 1993; Rogoff, 1996). Much of the literature has been directed toward explaining the expected excess return as arising from foreign exchange risk. Another branch of the literature has explored limits to capital mobility and frictions in asset markets. A third branch has looked at deviations from rational expectations. A line of research closely related to this paper has studied the role of the "convenience yield" in driving exchange rates. We discuss next these different strands of the literature.

Foreign exchange risk premium. Modeling failures of uncovered interest parity as arising from foreign exchange risk has a long history. Early contributions include Solnik (1974), Roll and Solnik (1977), Kouri (1976), Stulz (1981), and Dumas and Solnik (1995). Much theoretical work has been devoted to building models of the risk premium that are consistent with the Fama (1984) puzzle, which finds a positive correlation between the expected

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[4]This present value plays a key role in the analysis of Engel and West (2005), Froot and Ramadorai (2005), and Engel (2016). See Engel's(2014) survey of exchange rates for an overview of the risk premium's effect on exchange rates.

excess return and the interest rate differential.[5] Bansal and Shaliastovich (2013); Colacito (2009); Colacito and Croce (2011, 2013); Colacito, Croce, Gavazzoni, and Ready (2018); Colacito, Croce, Ho, and Howard (2018); and Lustig and Verdelhan (2007) examine models with recursive preferences. Verdelhan (2010) presents a model with habit formation to account for the Fama puzzle. Ilut (2012) proposes ambiguity aversion as a solution to the puzzle. Some recent studies, such as Burnside, Eichenbaum, Kleshchelski, and Rebelo (2011), Farhi and Gabaix (2016), and Farhi, Fraiberger, Gabaix, Ranciere, and Verdelhan (2015), model the risk premium as arising from rare disaster risk, following (Barro, 2006; Rietz, 1988).

Recent empirical work sheds light on the nature of the foreign exchange risk premium. Lustig, Roussanov, and Verdelhan (2014) identify a dollar risk factor that makes the dollar carry-trade profitable. Hassan and Mano (2019) distinguish between the factors that drive the dollar carry-trade and the cross-sectional deviations from uncovered interest parity. Kalemli-Özcan (2019) and Kalemli-Özcan and Varela (2021) note that the factors driving risk premia among advanced economies and those that do so in emerging markets are different.

An important development in the literature has been the modeling of the "safe haven" status of the US dollar and its association with the "exorbitant privilege" that the US enjoys from the returns on its net foreign asset position. Gourinchas and Rey (2007a,b) report findings that the US earns appreciably higher returns on its foreign investments than those earned by foreigners on investments in the US. Caballero, Farhi, and Gourinchas (2008) and Farhi and Maggiori (2018) offer models that help explain how the US is more able to "produce" safe assets that are valued by foreign investors but earn a lower expected return than foreign assets. Other papers have modeled the US as a country that is willing to assume more risk, perhaps because its internal financial markets are more developed and therefore willing to hold riskier assets that yield a higher expected return (see, for example, Mendoza, Quadrini, and Rios-Rull, 2009; Gourinchas, Rey, and Govillot, 2010; and Maggiori, 2017). Gourinchas, Rey, and Sauzet (2019) and Maggiori (2021) provide an overview of this literature.

Recent research has focused on the interaction between risk-averse investors and preferred habitat investors or noise traders, who may not be motivated by risk/return considerations in their portfolio choice. These studies include Koijen and Yogo (2020)' general model of portfolio choice, the preferred habitat models of Gourinchas, Ray, and Vayanos (2021), and Greenwood, Hanson, Stein, and Sunderam (2020), and the noise trader model

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[5]See Tryon (1979) and Bilson (1981) for earlier empirical studies that find this relationship. Engel (1996, 2014) surveys empirical and theoretical models.

of Itskhoki and Mukhin (2021a,b).

Limited capital mobility. Other models attribute these uncovered interest parity differentials to financial premia earned by foreign currency because of limited market participation, as in models in which order flow matters for exchange rate determination and requires some frictions in the foreign exchange market (see, for example Evans and Lyons 2002, 2008). Relatedly, Bacchetta and Van Wincoop (2010) posit that the slow adjustment of portfolios can account for the expected excess returns on foreign bonds.

An important recent literature has emphasized limited market participation (see the segmented markets models of Alvarez, Atkeson, and Kehoe, 2009 and Itskhoki and Mukhin, 2021a) or limited international arbitrage (Gabaix and Maggiori 2015; Amador, Bianchi, Bocola, and Perri 2020). While our model also brings financial intermediaries to the forefront, we do not introduce collateral constraints or other limits to lending that have been the subject of these papers.

The failure of covered interest parity since the global financial crisis is often interpreted as evidence of limits to arbitrage. See, for example, Baba and Packer (2009), Du, Tepper, and Verdelhan (2018), Avdjiev, Du, Koch, and Shin (2019), Liao (2020), and the survey of Du and Schreger (2021). Our study offers an alternative channel by which deviations from covered interest parity might arise.

Deviations from rational expectations. A simple alternative story for the UIP deviations is that agents' expectations are not fully rational. Empirical studies such as Frankel and Froot (1987), Froot and Frankel (1989), and Chinn and Frankel (2019) have used survey measures of expectations to uncover possible deviations from rational expectations. Kalemli-Özcan and Varela (2021) also find that the component of deviations from uncovered interest parity that is predictable from interest rate differentials may be driven by deviations from rational expectations. Models that incorporate systematically skewed expectations include Gourinchas and Tornell (2004) and Bacchetta and Van Wincoop (2006).

Convenience yield. Our model is closely connected to the recent examination of the "convenience yield"—the low return on riskless government liabilities—and exchange rates. We posit that our model provides one possible channel for the emergence of the convenience yield on US government bonds. See Engel (2016), Valchev (2020), Jiang, Krishnamurthy, and Lustig (2020, 2021), Engel and Wu (2018), and Kekre and Lenel (2021) for recent work featuring simple, descriptive models of the convenience yield. In particular, Jiang, Krishnamurthy, and Lustig (2021) and Kekre and Lenel (2021) provide equilibrium models in which the appreciation of the dollar is driven by an increase in its convenience yield and show how this can account for the potential resolution of reserve currency paradox docu-

mented in Maggiori (2017). Our study might be described as providing "microfoundations" for the convenience yield, which is essential for a deeper understanding of the factors that drive changes in the demand for US dollar assets and exchange rates. In particular, our model can account for why times of elevated funding risk translate into appreciations of the dollar and thus make the dollar a "safe haven".

Interbank markets and monetary policy. Our paper also relates to an emerging literature on interbank market frictions and monetary policy (see e.g. Bianchi and Bigio (2021); Piazzesi and Schneider (2021) and Weill (2020) for a review) To the best of our knowledge, our paper provides a first attempt at incorporating these frictions in an open economy framework. Our model builds more closely on Bianchi and Bigio (2021). We extend their model by considering multiple currencies and allowing for aggregate uncertainty.

Special role of the dollar. Finally, our paper is related to the literature on the pre-eminence of the dollar in international financial markets. Rey (2013, 2016) and Miranda-Agrippino and Rey (2020) identify US monetary policy's importance as a key factor in the global financial cycle. Gopinath (2016) and Gopinath, Boz, Casas, Díez, Gourinchas, and Plagborg-Møller (2020) stress the dominant role of the dollar unit of account as one key possible channel. Gopinath and Stein (2021) link invoicing patterns and the role of the dollar as a store of value. We propose a different channel based on the dominance of the dollar in the international financial system and argue that dollar funding risk has a significant effect on exchange rates.

Organization. The paper is organized as follows. Section 2 presents the empirical analysis. Section 3 presents the model, and Section 4 characterizes properties of the model. Section 5 presents the calibration of the model and the quantitative results. Section 6 concludes. All proofs are in the Appendix.

2 Empirical Analysis of Liquidity and Exchange Rates

We begin with a look at the data relating the banking sector's balance sheet and the foreign currency price of US dollars. Our thesis, at its simplest, is that the financial sector increases its demand for liquid dollar assets, including US government obligations and reserves held at the Federal Reserve, when funding becomes more uncertain, and this drives movements in exchange rates. Before the analysis, it is useful to provide some of the institutional background that underlies the thesis.

Institutional background. The US dollar serves as the leading funding currency. Close to half of all cross-border bank loans and international debt securities are denominated in dollars. In addition to serving as the key international unit of account, the dollar serves as

a vehicle currency for foreign exchange transactions and an invoicing currency for global trade. In fact, 85% of all foreign exchange transactions occur against the US dollar, and 40% of international payments are made in US dollars.[6,7]

The central role of the US dollar in the international financial and monetary system means that billions of US dollars circulate within and across countries every day. As the 2020 BIS working group report (Davies and Kent, 2020, p. 29) puts it,

> US dollar funding is channeled through the global financial system, involving entities across multiple sectors and jurisdictions. Participants in these markets face financial risks typically associated with liquidity, maturity, currency and credit transformation. What makes global US dollar funding markets special is the broad participation of non-US entities from all around the world. These participants are often active in US dollar funding markets without access to a stable US dollar funding base or to standing central bank facilities which can supply US dollars during episodes of market stress.

At the same time Ivashina, Scharfstein, and Stein (2015) note that "[European] banks rely on wholesale dollar funding, while raising more of their euro funding through insured retail deposits" (p. 1241), implying that dollar funding is more volatile and potentially less certain during times of instability.

The other pillar of our thesis is that financial institutions are subject to liquidity mismatch. To the extent that banks are not able to liquidate loans or other relatively illiquid assets, financial institutions' demand for dollars can fluctuate considerably, depending on funding risk and the vicissitudes of foreign exchange transactions. We will next argue that changes in these conditions translate in the data into movements in the dollar exchange rates.

Data and empirical analysis. We examine the behavior of the dollar against that of the other nine G10 currencies, with special attention given to the euro. The euro area is especially important in our analysis because it encompasses a large economy with a financial system that relies heavily on short-term dollar funding. The other currencies are the Australian dollar, the Canadian dollar, the Japanese yen, the New Zealand dollar, the Norwegian krone, the Swedish krona, the Swiss franc, and the UK pound.

We look at two sources of data for the US banking system. Detailed data on short-term dollar funding and on liquid dollar assets are not readily available for the global financial

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[6]See Davies and Kent (2020) and the references therein.

[7]The global status of the US dollar dates to the Bretton Woods agreement, and this dominance has only deepened since then (Ilzetzki, Reinhart, and Rogoff, 2019).

system, so we use the US data as a proxy for the dollar-denominated elements of the global banking balance sheets. That is, we assume that when faced with uncertainty about dollar funding, foreign banks' demand for liquid dollar assets responds in a similar way to that of banks located in the US (including US-based subsidiaries of foreign banks). This approach is also followed by Adrian, Etula, and Shin (2009), a study that aims to show how the price of risk is related to banks' balance sheets and the expected change in the exchange rate (rather than the current level of the exchange rate, which is our concern here). More precisely, Adrian, Etula, and Shin focus on the state of the balance sheet at time t in forecasting $e_{t+1} - e_t$, as they are concerned with understanding the expected excess return on foreign bonds between t and $t + 1$. Our interest is in how changes in the balance sheet between $t - 1$ and t contribute to changes in the exchange rate between $t - 1$ and t—that is, $e_t - e_{t-1}$.

We consider two measures of short-term funding to financial intermediaries. The first, used by Adrian, Etula, and Shin (2009), is US dollar financial commercial paper, series DTBSPCKFM from Federal Reserve Economic Data (FRED). Another major source of short-term funding to U.S. banks is demand deposits, measured by DEMDEPSL from FRED. We construct a variable that measures the level of funding and the response of financial intermediaries to uncertainty about that funding. We look at the ratio of the sum of reserves held at Federal Reserve banks and government securities (Treasury and agency) held by commercial banks (the sum of RESBALNS and USGSEC from FRED) to short-term funding (DTBSPCKFM + DEMDEPSL from FRED). This variable is endogenous in our model, but its movements are a key indicator of how the demand for dollars is affected by the financial sector's demand for liquid assets when funding risk increases. As dollar funding becomes more volatile for banks, they will increase their ratio of safe dollar assets to liabilities. That in turn will lead to a global increase in dollar demand, leading to a dollar appreciation.

The model we build describes financial intermediaries and their demand for liquid dollar assets. We see the intermediaries as representing a global collection of financial institutions from the U.S. and the rest of the world, including money market funds, insurance firms, mutual funds, etc. However, we use proxies based on the U.S. banking system for two reasons. First, while certain measures of short-term assets and liquid liabilities for the U.S. banking system are readily available and easily reproducible, this is not the case for other financial intermediaries, including foreign banks. Second, different intermediaries have different institutional and legal constraints, and so even if all the data were available, there is no clear way to aggregate the short-term funding and liquid assets of all intermediaries. Thus, we argue it is preferable to use as a basis liquidity measures of the U.S. banking

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system.

Figure 1 plots this ratio of liquid government asset holdings to short-term funding of the financial sector.[8] During this period, bank government asset holdings balances rose from around 10 billion dollars in August 2008 to nearly 800 billion dollars one year later, then reached a peak of around 2.3 trillion dollars by late 2017. They gradually declined to 1.4 trillion dollars by the end of 2019. However, the liquidity ratio does not show movement anywhere near that magnitude. It is true that it rose during the onset of the global financial crisis, but for the most part, this movement was not driven by the increase in reserves, because demand deposits rose almost proportionately. Instead, a large part of the rise in the overall liquidity ratio was driven by a fall in financial commercial paper funding, which worked to lower the denominator of the ratio. Subsequently, even as reserves continuted to increase, the liquidity ratio fell. The liquidity ratio is not mechanically determined by a decision of the central bank to inject or drain reserves from the banking system. The policies of the central bank do affect the liquidity ratio, as our model explains, but from a mechanical standpoint, the immediate effect of, for example, an open market purchase of bonds by the Federal Reserve to increase reserves held by banks is an equal increase in their liquid assets. However, as individual banks choose their optimal liquidity ratio, interest rates for various forms of funding adjust, and the liquidity ratio for the banking system as a whole rebalances.

Empirical results. In Table 1, we present the parameter estimates of the regression:

$$\Delta e_t = \alpha + \beta_1 \Delta(LiqRat_t) + \beta_2(\pi_t - \pi_t^*) + \beta_3 LiqDepRat_{t-1} + \epsilon_t. \tag{1}$$

In this regression, $\Delta(x_t)$ means "the change from $t-1$ to t" in the variable x_t; e_t is the log of the exchange rate expressed as the G10 currency price of a US dollar; $LiqRat_t$ is the log of the liquidity ratio described above; $\pi_t - \pi_t^*$ is the difference between year-on-year inflation rates in each of the nine countries and the US. All data are monthly.[9] The inflation variable is meant to capture the effects of monetary policy on exchange rates. As much of the empirical literature has found, there is a negative relationship between the change in a country's inflation rate and its exchange rate. When inflation is rising in a country, under inflation-targeting regimes, markets anticipate future monetary tightening, and that leads to a currency appreciation.

If dollar funding risk is driving the $LiqRat_t$, then wealso expect a positive relationship

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[8]The figure also plots alternative measures described below.
[9]An exception is that inflation for Australia and New Zealand are reported only quarterly. We linearly interpolate the data to get monthly series.
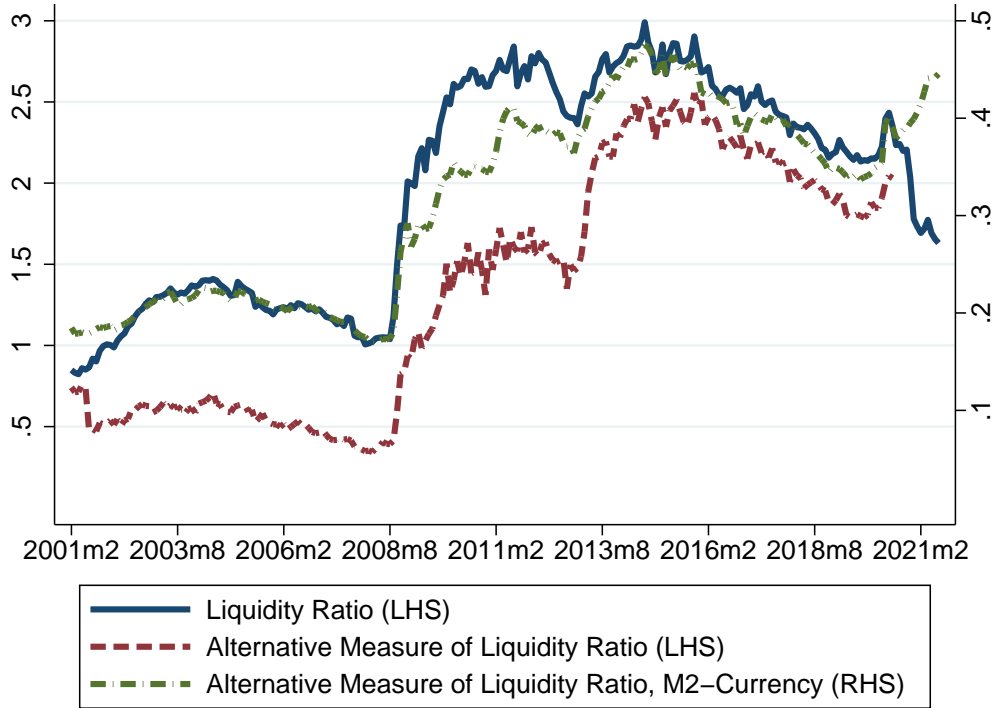
Figure 1: The Ratio of Liquid Assets to Short-Term Liabilities

between this variable and e_t; that is, β_1 should be positive. During times of high uncertainty, banks hold greater amounts of liquid dollar assets (reserves and Treasury securities) relative to demand deposits, hence $LiqRat_t$ is higher. That increased demand for safe dollar assets leads to a stronger dollar (an increase in e_t.)

We also include the lagged level of $LiqRat_t$. We do so because the depreciation of the dollar might depend on lagged as well as current levels of this variable. The regressions we report would have the same fit if we included current and lagged levels of this variable, instead of the change in the variable and the lagged level. We specify the regression as above for two reasons: First, specifying the regression so that the change in the liquidity variable influences the change in the exchange rate leads to a more natural interpretation. Second, while the current and lagged levels of the variable are highly correlated, which leads to multicollinearity and imprecise coefficient estimates, the change and the lagged level are much less correlated.

Table 1 reports the regression findings for the nine exchange rates. The sample period is February 2001 to July 2021. (Data on financial commercial paper start in January 2001.) With the exception of Japan, the liquidity ratio variable has the expected sign and is statistically significant at the 1% level for all exchange rates. The relative inflation variable also

has the correct sign for all the currencies and is statistically significant for most countries.

It is common to look at short-term interest rate movements to account for the effects of monetary policy changes on exchange rates. During much of our sample period, interest rates were near the zero lower bound, and they do not appear to do a good job measuring the monetary policy stance. We have included year-on-year inflation to capture the effects of inflation targeting through unconventional monetary policy through the market's anticipation of the policy response to past inflation. However, in Table A1 in the Appendix, we include $i_t - i_t^*$, the interest rate in each of the nine countries relative to the US, as a regressor. None of the major conclusions are altered by its inclusion, but the interest rate variables are mostly not statistically significant.

We highlight that the key regressor, $\Delta LiqRat_t$, is not simply a price variable, but a quantity variable. That is, these regressions above "explain" exchange rate movements but do not rely on other market prices to do the job. It is a balance sheet variable that plays the pivotal role.

We argue that funding risk drives the balance sheet variables, but a remaining concern is that funding risk is related to market uncertainty. What if we include a direct measure of uncertainty in the regressions? Many asset-pricing studies have used *VIX* to quantify market uncertainty, and *VIX* has explanatory power in accounting for the movements of many asset prices. However, *VIX* does not directly measure uncertainty about dollar funding for banks. Indeed, *VIX* might measure some dimensions of uncertainty, but it might also be capturing global risk, which might be driving the dollar, as in the model of Farhi and Gabaix (2016). Rey (2013) has found a strong correlation between *VIX* and private credit provided by banks, which suggests a dimension along which global risk might affect the economy through banks' intermediation function. In Table 2, we include the change in *VIX* along with the other variables.

As expected, *VIX* has positive coefficients in all cases (except again for Japan) and is statistically significant. An increase in *VIX* is associated with an appreciation of the dollar. However, the introduction of this variable does not reduce the significance of the liquidity ratio variable for any of the countries. For most, it has only a small effect on the magnitude of the coefficient. This suggests that the uncertainty that is quantified by *VIX* does not include all of the forces that drive the liquidity ratio and lead to its positive association with dollar appreciation. (Appendix Table A2 also includes the interest rate differential. As in Table A1, we see that its inclusion has little influence on the findings, and its effect is mostly small and insignificant.)

It is important to note that the liquidity ratio is not an exogenous driver of exchange

rates—neither in our model nor in the data. We will show that regressions based on simulated data from the model generate a positive association between the change in the liquidity ratio and the value of the dollar, in line with the empirical findings. Proposition 3 below shows that the regression coefficient will depend on the variance and persistence of the shocks. We note that much of the statistical significance of the liquidity ratio in this regression arises from the period of the Global Financial Crisis when funding to the financial system was particularly uncertain, which is in line with our model.

We can, however, use instrumental variables to isolate the effects of uncertainty on the liquidity ratio and their transmission to exchange rates. To that end, Table 3 uses two measures of uncertainty as instruments for the liquidity ratio: the cross-section standard deviation of the inflation rates of the G10 countries at each time period, and the cross-section standard deviation of the rates of depreciation for these currencies. The findings are largely the same as in Table 2. For most of the countries, the magnitude of the effect of the liquidity ratio on the exchange rate is increased, and for some (such as Canada), the statistical significance greatly increases. The model still fits the Japanese yen poorly, and we now find no statistical significance of the liquidity ratio on the Swiss franc exchange rate.

In Appendix Table A3, we take the alternative tack of including *VIX* as an instrument for the liquidity ratio. It is possible for *VIX* to be a valid instrument that is uncorrelated with the regression error, even though it is statistically significant when included in the regression separately (as in Tables 2 and 3) if the other forces that drive the liquidity ratio are uncorrelated with *VIX*. That is, Table A3 reports the influence of the liquidity ratio on exchange rates when the liquidity ratio is driven by *VIX* and other measures of uncertainty, while any other forces that might influence the exchange rate are relegated to the regression error. *VIX* is a valid instrument if it is uncorrelated with those forces. If one takes such a stance, then the estimates reported in Table A3 reveal a strong channel of uncertainty on exchange rates working through the liquidity ratio.

We considertwo alternative measures of the liquidity ratio. The first includes "net financing" of broker-dealer banks. This is a measure of "funds primary dealers borrow through all fixed-income security financing transactions," as described in Adrian and Fleming (2005). We include this as another source of short-term liabilities, similar to how net repo financing is included as a measure of short-term liabilities in the liquidity ratio calculated by the International Monetary Fund (2018). Figure 1 also plots this alternative measure of the liquidity ratio, which is smaller than our baseline measure because it includes another class of liabilities of the banking system in the US, while leaving the measure of liquid assets unchanged.

Tables A4, A5, 4, and A6 in the Appendix are analogous to Tables 1, 2, 3, and **??**, respectively. The conclusions using this alternative measure are virtually unchanged qualitatively, though of course the numerical values of the estimated coefficients are different. The liquidity ratio is still highly statistically significant for all currencies, except for Japan's, and, in the case of the instrumental variable regressions, Switzerland's.

Our empirical analysis also includes a third, broader measure of liabilities, the U.S. M2 money supply less currency in circulation. This measure then contains demand deposits, small-denomination time deposits and deposits in money market funds. It is plotted in 1, with the right-hand-side axis providing the correct scale. The liquidity ratio is smaller than the other two measures because it includes a broader measure of funding, but 1 shows that its movements are similar to the other two, though the proportional increase during the global financial crisis is not as steep. We estimate the models analogous to the ones reported above for the first two measures of the liquidity ratio, and display the results in A7, A8, 5, and A9. In all the regressions, we see the same pattern of positive coefficients on the liquidity ratio variable for all but one exchange rate. There are fewer statistically significant estimates in the OLS regressions, but the positive coefficients are strongly statistically significant in all cases except the Swiss franc in the instrumental variables estimates. We conclude that even with a very broad measure of funding to financial intermediaries, the proxy for the system's liquidity ratio has strong explanatory power for exchange rates.

Naturally, much of the power of the change in the liqudity ratio to account for changes in exchange rates comes during times when the global economy moves from quiescent to turbulent times, or vice-versa. While the global financial crisis is very helpful in identifying this relationship, it is not the only time period that pins down the estimates. We show this by estimating the model over two sub-samples. The first includes the period prior to the GFC, its subsidence, and the beginning of the European debt crisis, February 2001 to April 2012. The second period begins in May 2012, as markets begin to react to efforts salvage the euro and just pror to Mario Draghi's famous "do whatever it takes" speech in July 2012, and continues to the end our sample in July 2021. A10, A11, A12, and A13 report results for the first period, while the findings for the second period appear in A14, A15, A16, and A17. During the earlier period, with the exception of Japan, there is a statistically significant positive relationship between the change in the log liquidity ratio and the change in the log exchange rate for all currencies. The results are similar for the second period: the estimated coefficients on the liquidity ratio variable are positive for all but one of the currencies in the OLS and IV regressions. However, there are fewer statistically significant coefficient estimates, though as many as seven of the eight positive coefficients in the OLS estimates, and six of eight in the IV regressions are signficant at the 10 percent level or better.

Table 1: Exchange Rates and Liquidity Ratio Feb. 2001 – July 2021

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz
$\Delta(\text{LiqRat}_t)$	0.227***	0.256***	0.127***	-0.134***	0.287***	0.187***	0.212***	0.141***
	(4.839)	(4.106)	(2.723)	(-2.846)	(4.458)	(3.125)	(3.754)	(2.724)
$\pi_t - \pi_t^*$	-0.800***	-0.657***	-0.407**	0.011	-0.726***	-0.126	-0.465**	-0.565***
	(-3.972)	(-2.998)	(-1.982)	(0.084)	(-3.299)	(-0.873)	(-2.530)	(-2.644)
LiqRat_{t-1}	0.008*	0.005	0.007	0.002	0.004	0.010*	0.006	0.005
	(1.890)	(0.796)	(1.554)	(0.307)	(0.696)	(1.730)	(1.109)	(0.985)
Constant	-0.010***	-0.002	-0.006*	-0.001	-0.005	-0.007	-0.008**	-0.015***
	(-3.097)	(-0.595)	(-1.877)	(-0.120)	(-1.188)	(-1.618)	(-1.978)	(-2.966)
N	246	246	246	246	246	246	246	246
adj. R^2	0.11	0.07	0.03	0.02	0.09	0.03	0.06	0.03

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table 2: Exchange Rates and Liquidity Ratio and VIX Feb. 2001–July 2021

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz
$\Delta(\text{LiqRat}_t)$	0.198***	0.178***	0.082*	-0.119**	0.225***	0.137**	0.175***	0.126**
	(4.283)	(3.250)	(1.935)	(-2.528)	(3.762)	(2.429)	(3.206)	(2.426)
$\pi_t - \pi_t^*$	-0.668***	-0.386**	-0.278	-0.007	-0.523**	-0.051	-0.407**	-0.517**
	(-3.354)	(-2.008)	(-1.491)	(-0.050)	(-2.561)	(-0.382)	(-2.315)	(-2.411)
ΔVIX_t	0.124***	0.344***	0.220***	-0.077**	0.285***	0.239***	0.189***	0.064*
	(3.841)	(8.995)	(7.399)	(-2.350)	(6.792)	(6.116)	(4.991)	(1.784)
LiqRat_{t-1}	0.009**	0.006	0.007*	0.002	0.005	0.010*	0.007	0.005
	(2.059)	(1.204)	(1.770)	(0.306)	(0.995)	(1.877)	(1.330)	(1.047)
Constant	-0.010***	-0.004	-0.006*	-0.001	-0.006	-0.007*	-0.008**	-0.015***
	(-3.056)	(-1.104)	(-1.963)	(-0.193)	(-1.445)	(-1.697)	(-2.052)	(-2.833)
N	246	246	246	246	246	246	246	246
adj. R^2	0.16	0.30	0.21	0.04	0.23	0.16	0.14	0.04

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table 3: Exchange Rates and Liquidity Ratio Instrumental Variable Regression:
StDev(Inf) and StDev(XRate) instrument for Δ(LiqRat) Feb. 2001–July 2021

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz
$\Delta(\text{LiqRat}_t)$	0.488***	0.648***	0.477***	-0.312**	0.545***	0.528***	0.489***	0.012
	(3.322)	(3.558)	(3.504)	(-2.351)	(3.035)	(2.908)	(2.937)	(0.080)
$\pi_t - \pi_t^*$	-0.953***	-0.755***	-0.556**	0.080	-0.732***	-0.264	-0.598***	-0.397
	(-3.750)	(-2.932)	(-2.369)	(0.542)	(-3.021)	(-1.515)	(-2.846)	(-1.496)
LiqRat_{t-1}	0.012**	0.012*	0.014***	-0.003	0.009	0.018***	0.011*	0.003
	(2.530)	(1.948)	(2.649)	(-0.425)	(1.519)	(2.611)	(1.891)	(0.684)
ΔVIX_t	0.091**	0.292***	0.181***	-0.059	0.251***	0.200***	0.159***	0.076*
	(2.386)	(6.132)	(4.910)	(-1.639)	(5.235)	(4.335)	(3.685)	(1.932)
Constant	-0.014***	-0.008*	-0.012***	0.004	-0.009**	-0.013**	-0.013***	-0.011*
	(-3.506)	(-1.749)	(-2.922)	(0.583)	(-1.979)	(-2.504)	(-2.670)	(-1.709)
N	246	246	246	246	246	246	246	246

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table 4: Exchange Rates and Alternative Measure of Liquidity Ratio Instrumental Variable
Regression: StDev(Inf) and StDev(XRate) instrument for Δ(LiqRat2)

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz
$\Delta(\text{LiqRat2}_t)$	0.362***	0.491***	0.352***	-0.239*	0.411**	0.450***	0.373**	0.018
	(2.758)	(2.791)	(3.033)	(-1.872)	(2.579)	(2.625)	(2.593)	(0.146)
$\pi_t - \pi_t^*$	-0.607***	-0.548**	-0.403	0.100	-0.698***	-0.324	-0.552**	-0.490
	(-2.991)	(-2.065)	(-1.573)	(0.483)	(-2.996)	(-1.496)	(-2.347)	(-1.630)
LiqRat2_{t-1}	0.008**	0.008*	0.007**	0.000	0.007*	0.011**	0.007*	0.003
	(2.318)	(1.966)	(2.124)	(0.091)	(1.832)	(2.310)	(1.795)	(1.087)
ΔVIX_t	0.001***	0.004***	0.002***	-0.001*	0.003***	0.002***	0.002***	0.001**
	(2.617)	(6.194)	(5.240)	(-1.693)	(5.402)	(4.018)	(3.955)	(2.146)
Constant	-0.007***	-0.002	-0.004	0.002	-0.005*	-0.003	-0.007**	-0.011*
	(-2.717)	(-0.832)	(-1.636)	(0.484)	(-1.839)	(-1.137)	(-2.146)	(-1.945)
N	234	232	234	234	232	234	234	234

t statistics in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

3 A Model of Banking Liquidity and Exchange Rates

We present a dynamic equilibrium model of global banks that intermediate international financial flows and are subject to idiosyncratic liquidity shocks. The model has two economies, the EU and the US, with corresponding currencies and central banks. To fix ideas, we think about the euro as the domestic currency and the dollar as the foreign currency. There is a representative global household and a single final tradable good

Table 5: Relationship of Exchange Rates and Alternative Measure of Banking Liquidity Ratio (M2-Currency) Instrumental Variable Regression: StDev(Inf) and StDev(XRate) instrument for Δ(LiqRat3)

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz
$\Delta(\text{LiqRat3}_t)$	0.766***	1.043***	0.761***	-0.449**	0.966***	0.853***	0.773***	0.029
	(2.930)	(3.153)	(3.326)	(-2.209)	(2.762)	(2.781)	(2.694)	(0.121)
$\pi_t - \pi_t^*$	-0.807***	-0.719**	-0.477**	0.013	-1.034***	-0.219	-0.535**	-0.381
	(-2.917)	(-2.488)	(-2.002)	(0.096)	(-3.045)	(-1.238)	(-2.401)	(-1.490)
LiqRat3_{t-1}	0.009	0.011	0.013**	0.004	0.007	0.018**	0.011	0.005
	(1.517)	(1.525)	(2.169)	(0.684)	(0.995)	(2.285)	(1.613)	(0.929)
ΔVIX_t	0.149***	0.367***	0.236***	-0.093***	0.306***	0.260***	0.215***	0.078**
	(3.709)	(7.462)	(6.417)	(-2.865)	(6.273)	(5.600)	(4.819)	(2.178)
Constant	0.004	0.011	0.011	0.006	0.004	0.018*	0.006	-0.003
	(0.475)	(1.225)	(1.535)	(1.050)	(0.402)	(1.967)	(0.676)	(-0.378)
N	246	246	246	246	246	246	246	246

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

produced by a continuum of global multinationals.

3.1 Environment

Timing. Time is discrete and of an infinite horizon. Every period is divided in two sub-stages: a lending stage and a balancing stage. In the lending stage, banks make their equity payout, Div_t, and portfolio decisions. In the balancing stage, banks face liquidity shocks and re-balance their portfolio.

Notation. We use an asterisk to denote the foreign currency (i.e., the dollar) variable and a bar to denote a real variable. The vector of aggregate shocks is indexed by X. The exchange rate is defined as the amount of euros necessary to purchase one dollar—hence, a higher e indicates an appreciation of the dollar.

Preferences and budget constraint. Banks' payouts are distributed to households that own shares and have linear utility with discount factor β. A bank's objective is to maximize shareholders' value, and therefore it maximize the net present value of dividends:

$$\sum_{t=0}^{\infty} \beta^t \cdot Div_t. \tag{2}$$

Banks enter the lending stage with a portfolio of assets and liabilities and collect and make the associated interest payments. The portfolio of initial assets is given by liquid assets, m_t

and m_t^*, which are in both euros and dollars, and loans b_t, denominated in consumption goods. Note that we refer to liquid assets as "reserves" for simplicity, but this term should be understood as also encompassing government bonds—the important property, as we will see, is that these are assets that can be used as settlement instruments.[10]

On the liability side, banks obtain funding via demand deposits, d_t and d_t^*, discount window loans, w_t and w_t^*, and net interbank loans, f_t and f_t^* (which are negative if the bank has lent funds). Deposit and interbank market loans have market returns given by i^d and $\bar{i}^f$, while central banks set the corridor rates for reserves and the discount window, which are i^m and i^w, respectively. A yield i_t paid in period t is pre-determined in period $t-1$. Meanwhile, R^b is the real return on loans.

The bank's budget constraint, expressed in foreign currency, is then given by

$$
P_t^* Div_t + \frac{m_{t+1} - d_{t+1}}{e_t} + b_{t+1}P_t^* + m_{t+1}^* - d_{t+1}^* \leq P_t^* b_t R_t^b + m_t^*(1 + i_t^{m,*}) - d_t^*(1 + i_t^{d,*})
$$

$$
- f_t^*(1 + i_t^{f,*}) - w_t^*(1 + i_t^{w,*}) + \frac{m_t(1 + i_t^m) - d_t(1 + i_t^d) - f_t(1 + i_t^f) - w_t(1 + i_t^w)}{e_t}. \quad (3)
$$

Withdrawal shocks. In the balancing stage, banks are subject to random withdrawal of deposits in either currency. As in Bianchi and Bigio (2021), withdrawals have zero mean—hence deposits are reshuffled but preserved within the banking system. Here, we also assume in addition that the economy features aggregate risk. In particular, we assume that the distribution of these shocks is time varying—below we describe other aggregate shock. In particular, withdrawal shocks, denoted by ω, are drawn from a continuous distribution with CDF and PDF denoted by Φ_t and ϕ_t respectively. When $\omega > 0$, a bank receives an inflow of deposits and when $\omega < 0$, a bank faces an outflow of deposits.

The inflow and outflow of deposits across banks generates, in effect, a transfer of liabilities. We assume that these transfers are settled using reserves of the corresponding currency. Importantly, reserves must remain positive at the end of the period. We denote by s_t^j the euro reserve balances of a bank upon facing a withdrawal shock ω_t^j. This balance is given by the amount of euro reserves a bank brings from the lending stage minus the

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[10]That is, our analysis is not about the management of scarce reserves per se, but more broadly about liquidity management. As it is often discussed, banks have had abundant excess reserves for the most part since the 2008 financial crisis—see however, the work by Copeland, Duffie, and Yang (2021) showing that reserves at various points in the post-crisis period were not so ample owing to the series of new liquidity regulations. In any case, liquidity concerns have remained a first-order concern for financial institutions, as evidenced by observed measures of liquidity premia as well as the Senior Financial Officer Survey, which is our focus here.

withdrawals of deposits:

$$s_t^j = m_{t+1} + \omega_t^j d_{t+1}. \tag{4}$$

We omit the superscript from bank portfolio choices because it is without loss of generality that all banks make the same choices in the lending stage.[11] Higher liquidity holdings m_{t+1} makes it more likely that the bank will end with a surplus. If a bank faces a withdrawal shock lower than $-m/d$, it will end with a deficit reserve balance. Otherwise, the bank has a surplus. Similarly, we have the following balances in dollars: $s_t^{j,*} = m_{t+1}^* + \omega_t^{j,*} d_{t+1}^*$.

Interbank market. After the withdrawal shocks are realized, there is a distribution of bank surplus balances and bank deficit balances in both currencies. We assume that there is an interbank market for each currency, in which banks that have a deficit balance in one currency borrow from those that have a surplus balance in that currency. These two interbank markets behave symmetrically, so it suffices to show only how one of them works.[12]

We model the interbank market as an over-the-counter (OTC) market, in line with institutional features of this market (see Ashcraft and Duffie, 2007 and Afonso and Lagos, 2015). Modeling the interbank market using search and matching is also natural, considering that the interbank market is a credit market in which banks on different sides of the market—surplus and deficit—must find a counterparty they trust. Our specific formulation follows Bianchi and Bigio (2017; 2021) which in turn blends features from Atkeson, Eisfeldt, and Weill (2015) and Afonso and Lagos (2015).

As a result of the matching frictions, only a fraction of an individual bank's surplus (deficit) is lent (borrowed) in the interbank market. A bank with surplus s^j is able to lend a fraction Ψ_t^+ to other banks. The remainder surplus is kept in reserves. Conversely, a bank that has a deficit is only able to borrow a fraction Ψ_t^- from other banks, and the remainder deficit is borrowed at a penalty rate i_t^w. The penalty rate can be thought of as the discount window rate or as an overdraft rate charged by correspondent banks that have access to the Fed's discount window.

The fractions Ψ_t^+ and Ψ_t^- are endogenous and depend on the aggregate reserve deficit blances relative to surplus balances. Assuming a constant returns to scale matching function, the probabilities depend entirely on market tightness, defined as $\theta_t \equiv S_t^- / S_t^+$, where

---

[11]As we will show below, the portfolios are indeterminate for an individual bank. Deposits, credit and reserves are determined only in the aggregate.

[12]We assume a stark form of segmented interbank markets: dollar surpluses cannot be used to patch euro deficits and vice versa. This assumption can be relaxed to some extent, but some form of segmentation of asset markets is necessary both to obtain liquidity premia and to rule out Kareken and Wallace (1981)'s exchange rate indeterminacy. In Section 4.4, we discuss an extension of the baseline model along this line.

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$S_t^+ \equiv \int_0^1 \max\{s_t^j, 0\}\, dj$ and $S_t^- \equiv -\int_0^1 \min\{s_t^j, 0\}\, dj$ denote the aggregate surplus and deficit, respectively. Notice that because $m \geq 0$ and $\mathbb{E}(\omega) = 0$, we have that in equilibrium, $\theta \leq 1$. That is, there is a relatively larger mass of banks in surplus than deficit.

The interbank market rate is the outcome of a bargaining problem between banks in deficit and those in surplus. There are multiple trading rounds, in which banks trade with each other. If banks are not able to match by the trading rounds, they deposit the surplus of reserves at the central bank or borrow from the discount window. Throughout the trading, the terms of trade at which banks borrow and lend—that is, the interbank market rate—depend on the probabilities of finding a match in a future period.[13] We used i^f in the budget constraint (9) to denote the average interbank market rate at which banks trade. Ultimately, we can define a liquidity yield function χ that captures the benefit of having a real surplus $\tilde{s}$ (or the cost of having a real deficit) upon facing the withdrawal shock as follows:

$$\chi(\theta, \tilde{s}; X, X') = \begin{cases} \chi^+(\theta; X, X')\tilde{s} & \text{if } \tilde{s} \geq 0, \\ \chi^-(\theta; X, X')\tilde{s} & \text{if } \tilde{s} < 0 \end{cases} \tag{5}$$

where χ^+ and χ^- are given by

$$\chi^-(\theta; X, X') = \Psi^-(\theta)[R^w(X, X') - R^f(X, X')] + (1 - \Psi^-(\theta))[R^w(X, X') - R^m(X, X')], \tag{6}$$

$$\chi^+(\theta; X, X') = \Psi^+(\theta)[R^f(X, X') - R^m(X, X')]. \tag{7}$$

In these expressions, $R^y(X, X')$ denotes the realized real rate of an asset or liability y when the initial state is X and the next period state is X'. Recall that the nominal rate is pre-determined, but the realized real return depends on the inflation rate. In particular, we have that $R^y(X, X') \equiv (1 + i^y(X))/(1 + \pi(X, X'))$, where $\pi(X, X') \equiv P(X')/P(X) - 1$ denotes the inflation rate. When it does not lead to confusion, we streamline the argument (X, X') in these expressions. We will also use 'bars' to denote expected returns. That is, $\bar{R}^y \equiv \mathbb{E}[R^y(X, X')|X]$ and $\bar{\chi} = \mathbb{E}[\chi(\theta, \tilde{s}; X, X')|X]$.

Equation (6) reflects that a bank that borrows from the the interbank market or from the discount window obtains the interest on reserves—hence, the cost of being in deficit is given by $R^f - R^m$ in the former and $R^w - R^m$ in the latter. By the same token, (6) reflects that the benefit from lending in the interbank market in the case of surplus is $R^f - R^m$.

Figure 2 presents a sketch of the timeline of decisions within each period. We next

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[13]Multiple trading rounds imply that interbank market rates vary with the tightness of the interbank market. With a single trading round, the interbank market rate would be a constant that depend on policy rates but not on the interbank-market tightness.
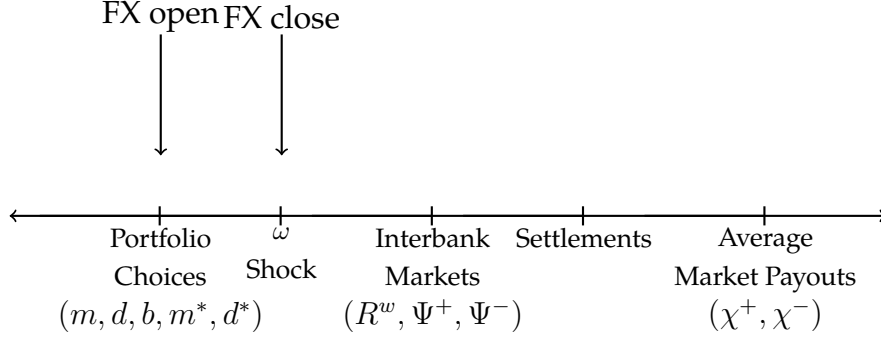
Figure 2: Timeline

describe the bank optimization problem.

Banks' problem. The objective of a bank is to choose dividends and portfolios to maximize (2) subject to the budget constraint. Critically, when choosing the portfolio, banks anticipate how withdrawal shocks may lead to a surplus or deficit of reserves and the associated costs and benefits of ending with these positions. We express the bank's optimization problem in terms of real portfolio holdings $\{\tilde{b}, \tilde{m}^*, \tilde{d}^*, \tilde{d}, \tilde{m}\}$ and the real returns. Thus, we define $\tilde{x}_t \equiv x_t / P_{t-1}$. The individual state variable is net worth, n, defined as the value of the real assets minus liabilities at the beginning of the period. Given the initial net worth, the bank problem consists of choosing the real portfolio and its dividends Div to maximize its value. Recursively, the bank problem is:

$$v\left(n, X\right) = \max_{\{Div, \tilde{b}, \tilde{m}^*, \tilde{d}^*, \tilde{d}, \tilde{m}\}} Div + \beta \mathbb{E}\left[v\left(n', X'\right)\right] \tag{8}$$

subject to the budget constraint

$$Div + \tilde{b} + \tilde{m}^* + \tilde{m} = n + \tilde{d} + \tilde{d}^*, \tag{9}$$

where the evolution of bank net worth is given by

$$n' = \underbrace{R^b(X)\tilde{b} + R^m(X, X')\tilde{m} + R^{m,*}(X, X')\tilde{m}^* - R^d(X, X')\tilde{d} - R^{*,d}(X, X')\tilde{d}^*}_{\text{Portfolio Returns}}$$
$$+ \underbrace{\chi^*(\theta^*(X), \tilde{m}^* + \omega^* \tilde{d}^*; X, X') + \chi(\theta(X), \tilde{m} + \omega \tilde{d}; X, X')}_{\text{Settlement Costs}}. \tag{10}$$

The evolution of n depends on the realized return on assets, but also on the realized settlement costs.[14] Because of the linearity of the banks' payoffs and the objective function, the value function is linear in net worth. Anticipating that in general equilibrium, there is a finite demand for loans and deposits, we note that an equilibrium therefore requires that $R^b(X) = 1/\beta \geq R^m(X, X')$.[15] The next lemma is an intermediate step toward the solution of the bank under this condition.

Lemma 1. *The solution to* (8) *is* $v(n, X) = n$, *and the optimal portfolio* $\{\tilde{m}, \tilde{d}, \tilde{m}^*, \tilde{d}^*\}$ *solves*

$$\Pi(X) = \max_{\{\tilde{m}, \tilde{d}, \tilde{m}^*, \tilde{d}^*\}} \mathbb{E}\Big\{ \big[R^b(X) - R^d(X, X')\big] \tilde{d} - \big[R^b(X) - R^m(X, X')\big] \tilde{m}$$
$$\big[R^b(X) - R^{*,d}(X, X')\big] \tilde{d}^* - \big[R^b(X) - R^{*,m}(X, X')\big] \tilde{m}^*$$
$$\Big[\chi(\theta(X), \tilde{m} + \omega\tilde{d}; X, X')\Big] + \Big[\chi^*(\theta^*(X), \tilde{m}^* + \omega^*\tilde{d}^*; X, X')\Big]\Big] \Big\}. \quad (11)$$

The first two lines in (11) represent the direct portfolio payoffs. In this case, only the expectation over aggregate shocks is relevant. The second line constitutes the expected liquidity costs/benefits, which depend on the portfolio of the bank and the idiosyncratic withdrawal risk.

The bank portfolio problem is homogeneous of degree one. Thus, it must be that in general equilibrium, expected real returns are such that $\Pi(X) = 0$ and the scale of the portfolio is indeterminate at the individual bank level. Otherwise, banks could scale their portfolio and obtain unbounded profits. On the other hand, the liquidity ratio is determined. In effect, the kink in the liquidity cost function creates concavity in the bank objective and risk-averse behavior. Finally, like the scale of the portfolio, dividends and leverage are indeterminate at the individual level but determined at the aggregate level.

Non-financial sector. This section describes the non-financial block. This block is composed of households that supply labor and save in deposits in both currencies. Some goods must be purchased using deposits. Namely, some goods are purchased only with dollar deposits, some are purchased only euro deposit, and some goods don't require any means of payment. Firms are multinationals that use labor to produce the final good and are subject to working capital constraints, giving rise to a demand for loans. Goods trade is costless and as a result, the law of one price holds. This block delivers endogenous schedules for loan demand and

---

[14]To obtain (10), we use the definition of χ as expressed in (5)-(6) and the real returns. Implicit in the law of motion for net worth is the convention that a bank that faces a withdrawal covers the associated interest payments net of the interest on reserves.

[15]If the return on loans were lower than $1/\beta$, banks would not invest in loans. Conversely, if the return on loans (or reserves) were higher than $1/\beta$, banks would inject infinite equity in the bank, and the bank's value would be infinite.

deposits in both currencies.

To keep the model simple, we make assumptions so that the effective loan demand and deposit supplies are static. In Appendix E, we obtain the following schedules for the real aggregate loan demand by firms, B_t^d, and real aggregate deposit supply for deposits in euros and dollars, D_t^s and $D_t^{*,s}$:

$$B_t^d = \Theta_t^b \left(R_{t+1}^b \right)^{\epsilon^b}, \qquad \epsilon^b < 0, \quad \Theta_t^b > 0, \tag{12}$$

$$D_{t+1}^s = \Theta_t^d \left(\bar{R}_{t+1}^d \right)^{\epsilon^d}, \qquad \epsilon^d > 0, \quad \Theta_t^d > 0, \tag{13}$$

$$D_{t+1}^{*,s} = \Theta_t^{*,d} \left(\bar{R}_{t+1}^{*,d} \right)^{\epsilon^{d*}}, \quad \epsilon^{d*} > 0, \quad \Theta_t^{*,d} > 0, \tag{14}$$

where ϵ^b is the semi-elasticity of credit demand and $\{\epsilon^d, \epsilon^{d*}\}$ are the semi-elasticities of the deposit supplies with respect to the real returns, while the Θ terms are scale coefficients. These parameters are linked to the production structure and preference parameters in the micro-foundation.

Government/Central Bank. The two central banks choose the nominal rates for reserves, i_t^m, and the discount window, i_t^w, as well as the nominal supply of reserves $\{M_{t+1}, M_{t+1}^*\}$ and nominal discount window loans W_t. To balance the payments on reserves and the revenues from discount window loans, we assume that central banks passively adjust lump sum taxes (or transfers). Because households have linear utility in the special good, these lump sum taxes have no implications. We have the following budget constraint for the euro:

$$M_{t+1} + T_t - W_{t+1} = M_t(1 + i_t^m) - W_t(1 + i_t^w). \tag{15}$$

An identical budget constraint holds for the dollar.

We note that we only consider one type of government liability: we not not distinguish between government bonds and central bank reserves. Our analysis, however, can be immediately extended to allow for a meaningful distinction between reserves and government bonds, following Bianchi and Bigio (2021).

3.2 Equilibrium

We study recursive competitive equilibria in which all variables are indexed by the vector of aggregate shocks, X. We consider shocks to the nominal interest rates on reserves, the deposit supply, and the volatility of withdrawals. Without loss of generality, we restrict to a symmetric equilibrium, in which all banks choose the same portfolios.

Definition 1. Given central bank policies for both countries $\{M(X), i^m(X), i^w(X), W(X)\}$,

$\{M^*(X), i^{m,*}(X), i^{w,*}(X), W^*(X)\}$, a recursive competitive equilibrium is a pair of price level functions $\{P(X), P^*(X)\}$, exchange rates $e(X)$, real returns for loans $R^b(X)$, nominal returns for deposits $\{i^d(X), i^{d,*}(X)\}$, an interbank market rate $i^f(X)$, market tightness $\theta(X)$, bank portfolios $\{\tilde{d}(X), \tilde{d}^*(X), \tilde{m}(X), \tilde{m}^*(X), \tilde{b}(X)\}$, interbank and discount window loans $\{f(X), f^*(X), w(X), w^*(X)\}$, and aggregate quantities of loans $\{B(X)\}$ and deposits $\{D(X), D^*(X)\}$ such that

(i) Banks choose portfolios $\{\tilde{d}(X), \tilde{d}^*(X), \tilde{m}(X), \tilde{m}^*(X), \tilde{b}(X)\}$ to maximize expected profits, as stated in (11).

(ii) Households are on their deposit supply and firms are on their loan demand. That is, equations (12)-(13) are satisfied given real returns and quantities $\{B(X), D(X), D^*(X)\}$.

(iii) The law of one price holds $P(X) = P^*(X)e(X)$.

(iv) Markets clear for deposits $\tilde{d}(X) = D^s(X)$ and $\tilde{d}^*(X) = D^{s,*}(X)$; reserves $\tilde{m}(X)P(X) = M(X)$ and $\tilde{m}^*(X)P^*(X) = M^*(X)$; loans $\tilde{b}(X) = B(X)$; and the interbank markets $\Psi^+(X)S^+ = \Psi^-(X)S^-$ and $\Psi^{+,*}(X)S^{+,*} = \Psi^{-,*}(X)S^{-,*}$.

(v) For both currencies, market tightness $\theta(X)$ is consistent with the portfolios and the distribution of withdrawals, while the matching probabilities $\{\Psi^+(X), \Psi^-(X)\}$ and interbank market rates $i^f(X)$ are consistent with market tightness $\theta(X)$.

4 Characterization

4.1 Liquidity Premia and Exchange Rates

We first describe the exchange rate determination. We combine both reserve-market clearing conditions, the law of one price, and the deposit clearing conditions, to arrive at a condition for the determination of the nominal exchange rate:

$$e(X) = \frac{P(X)}{P^*(X)} = \frac{M(X)/\tilde{m}(X)}{M^*(X)/\tilde{m}^*(X)}. \tag{16}$$

Condition (16) is a Lucas-style exchange rate determination equation, but rather than following from cash-in-advance constraints, it is derived from banks' liquidity management decisions. Given a real demand for reserves in euros and dollars that emerges from the bank portfolio problem (11), the dollar will be stronger (i.e., higher e) the larger is the nominal supply of euro reserves relative to that of dollar reserves. Similarly, for given nominal supplies of euro and dollar reserves, the dollar will be stronger the larger is the

relative demand for real dollar reserves. The novelty relative to the canonical Lucas-style model is that liquidity factors play a role in the real demand for currencies, and hence they affect the value of the exchange rate. We now turn to analyzing the determinants of the real demand for reserves in each currency.

To understand how liquidity factors affect the exchange rate through the demand for reserve balances, let us inspect the portfolio problem (11). We denote by $\mu = \tilde{m}/\tilde{d}$ the banks' liquidity ratio and note that $s^j < 0$ if and only if $\omega^j < -\mu$. Using the expression for the liquidity yield function (5), and recalling that 'bars' denote expected returns, we can express the first-order condition with respect to $\tilde{m}$ as

$$R^b - \bar{R}^m = (1 - \Phi(-\mu))\bar{\chi}^+(\theta) + \Phi(-\mu)\bar{\chi}^-(\theta). \tag{17}$$

At the optimum, banks equate the expected real marginal return on loans, R^b, with the expected real marginal return on reserves. The latter is given by the expected real interest on reserves $\bar{R}^m$ plus a random marginal liquidity value. If the bank ends up in surplus, which occurs with probability $1 - \Phi(-\mu)$, the expected real marginal value is $\bar{\chi}^+$. If the bank ends up in deficit, which occurs with probability $\Phi(-\tilde{m}/\tilde{d})$, the expected real marginal value is $\bar{\chi}^-$ (because the bank spares the marginal cost of borrowing in the interbank market). We label the difference in yields as the bond premium, $\mathcal{BP} \equiv R^b - \bar{R}^m$ and similarly $\mathcal{BP}^* \equiv R^b - \bar{R}^{m,*}$.

We have an analogous condition for m^*:

$$R^b - \bar{R}^{m,*} = (1 - \Phi^*(-\mu^*))\bar{\chi}^{+,*}(\theta^*) + \Phi^*(-\mu^*)\bar{\chi}^{-,*}(\theta^*). \tag{18}$$

Combining (17) and (18) and using the law of one price $1 + \pi = \mathbb{E}\left[(1 + \pi^*)e'/e\right]$, we obtain a *liquidity premium adjusted interest parity condition*. In particular, denoting the total derivative of $\bar{\chi}$ with respect to m (i.e., the right-hand side of 17) by $\bar{\chi}_{m^*}(s^*; \theta^*)$, we have that

$$\mathbb{E}_t\left\{\frac{1}{1 + \pi_{t+1}}\left[1 + i_t^m - (1 + i_t^{m,*}) \cdot \frac{e_{t+1}}{e_t}\right]\right\} = \underbrace{\mathbb{E}\left[\bar{\chi}_{m^*}(s^*; \theta^*) - \bar{\chi}_m(s; \theta)\right]}_{\mathcal{DLP}}. \tag{19}$$

This equation establishes that the difference in the real return on reserves in the two currencies is equal to the difference in the marginal liquidity values. We refer to the difference in marginal liquidity values as the dollar liquidity premium, the variable $\mathcal{DLP}$.

Without a dollar liquidity premium, (19) would reduce to a canonical UIP that equates, to a first order, the difference in nominal returns to the expected depreciation. However, whenever the marginal liquidity value of a dollar is larger than that of a euro (i.e., when

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$\mathcal{DLP} > 0$), a lower nominal interest rate in dollars that in euros is consistent with equilibrium, even if the exchange rate is expected to be constant. Note that because banks are risk neutral, there is no risk premium, and the deviation from UIP emerges entirely through liquidity. A way to capture the special role of the dollar in short-term funding, which we discussed in Section 2, is to assume that dollar funding is riskier than in euros. When this is the case, the dollar commands a convenience yield.

Finally, we have the first-order conditions with respect to deposits in both currencies:

$$R^d = \bar{R}^m + \mathbb{E}_\omega \left[\bar{\chi}_m \left(s; \theta \right) - \bar{\chi}_d \left(s; \theta \right) \right] \text{ and } \bar{R}^{d,*} = \bar{R}^{m,*} + \mathbb{E}_{\omega^*} \left[\bar{\chi}_{m^*} \left(s^*; \theta^* \right) - \bar{\chi}_{d^*} \left(s^*; \theta^* \right) \right]. \quad (20)$$

where $\bar{\chi}_d$ denotes the total derivative of $\bar{\chi}$ with respect to d. Like (19), these conditions imply that the expected real return on dollar and euro deposits may not be equated. In particular, a higher marginal liquidity cost of dollar deposits will be a force towards a lower real return of dollar deposits.

4.2 Effects of Shocks

We now examine how the exchange rate and liquidity premia vary with various shocks. Toward an analytical characterization, it is convenient to momentarily assume that the supply of deposits is perfectly inelastic in both currencies. This assumption sharpens the results, but does not alter the essence of the mechanism, as we then show numerically.

We focus on how shocks to the dollar alter the exchange rate and the $\mathcal{DLP}$. The same shocks to the euro interbank market will carry the opposite effects. Moreover, because in this version of the model, R^b is constant and the deposit supplies are inelastic, shocks to the dollar will not affect $\mathcal{BP}$. By contrast, the $\mathcal{DLP}$ will move in tandem with $\mathcal{BP}^*$, a result that speaks directly to a literature connecting the liquidity premium within dollar denominated assets to the exchange rate (Liao, 2020; Jiang, Krishnamurthy, and Lustig, 2021; Engel and Wu, 2018).

A useful object to characterize the effects of various shocks is the derivative of the $\mathcal{DLP}$ with respect to the dollar liquidity ratio:

$$\mathcal{DLP}_{\mu^*} = \underbrace{\left(\left(1 - \Phi^*(-\mu^*) \right) \cdot \bar{\chi}_{\theta^*}^{*,+} + \Phi^*(-\mu^*) \cdot \bar{\chi}_{\theta^*}^{*,-} \right) \cdot \frac{\partial \theta^*}{\partial \mu^*}}_{\text{effect on average interbank rates}} - \underbrace{\phi^*(-\mu^*) \cdot \left(\bar{\chi}^{*,-} - \bar{\chi}^{*,+} \right)}_{\text{liquidity risk exposure}} < 0.$$

This derivative captures are two effects. First, a higher liquidity ratio reduces the interbank-market tightness θ, thus easing the settlement frictions and reducing the average interbank rates. This general equilibrium effect reduces the liquidity premium. Second, a higher

liquidity ratio reduces the probability that a an individual bank ends with a deficit. Because the cost of deficits is higher than the benefit of surpluses, this partial equilibrium effect also reduces the liquidity premium.

With this expression in hand, we are to characterize the effects of a shocks.

Shocks to supply of dollar funding. A first question of interest is what are the effects of an increase in the funding of banks denominated in dollars. Since the deposit supply is inelastic, we can think of this as a shock to the quantity of D^*—with an elastic supply, this is a shock to the scale Θ^*.

Proposition 1 (Funding level shock). *Consider an increase in the real supply for dollar deposits. We have the following:*

1) If the shock is i.i.d, then the shock appreciates the dollar, reduces the dollar liquidity ratio, and raises the $\mathcal{DLP}$. In particular,

$$\frac{d \log e}{d \log D^*} = -\frac{\mathcal{DLP}_{\mu^*}}{R^b - \mathcal{DLP}_{\mu^* \mu^*}} \in (0, 1), \quad \frac{d \log \mu^*}{d \log D^*} = -\frac{R^b}{R^b - \mathcal{DLP}_{\mu^* \mu^*}} \in (-1, 0),$$

and $d\mathcal{DLP} = \bar{R}^{m,*} d \log e > 0$.

2) If the shock is permanent, then the shock appreciates the dollar one for one, and does not changet the liquidity ratio nor the $\mathcal{DLP}$:

$$\frac{d \log e^*}{d \log D^*} = -\frac{d \log P^*}{d \log D^*} = 1, \quad and \quad d\mu^* = d\mathcal{DLP} = 0.$$

Proposition 1 establishes that a higher supply of dollar deposits appreciates the dollar regardless of whether the shock is temporary or permanent. The logic is simple: a higher amount of real dollar deposits increases the demand for real dollar reserves. As banks have more dollar liabilities, there is a higher marginal value from dollar reserves. Given a fixed nominal supply of reserves, the increase in demand leads to an appreciation of the dollar.

The increase in the supply of dollar deposits has different implications for liquidity premia depending on whether the shock is temporary or permanent. When the shock is temporary, the exchange rate is expected to revert to the lower initial value in the following period. Given nominal rates, this reduces the expected real return of holding dollar reserves and the demand for dollar reserves fall for an individual bank. In equilibrium, dollar reserves must have a higher marginal liquidity value, and there is a rise in the $\mathcal{DLP}$. Overall, we then have that a temporary increase in the supply of dollar deposits, the dollar appreciates, the dollar liquidity ratio falls, and the $\mathcal{DLP}$ increases.

When the shock is permanent, the effect on the exchange rate is also expected to be

permanent. In the absence of any expected depreciation effects, the $\mathcal{DLP}$ must remain constant. Thus, in equilibrium, the outcome is that banks increase their holdings of dollar reserves in real terms in proportion to the increase in the supply of deposits. Since the supply of M^* is fixed, the amount of goods that can be bought with one dollar must increase, and this appreciates the dollar.[16]

Shocks to dollar funding risk. Next, we characterize the effects of a rise in funding risk. For that purpose, it is useful to index Φ by a parameter that captures the volatility of withdrawals, σ. We use the following index:

Assumption 1. *The distribution of shocks $\Phi^*(\omega; \sigma^*)$ satisfies $\Phi^*_{\sigma^*}(\omega; \sigma^*) > 0$ for any $\omega < 0$.*

This assumption provides an ordering to a family of distributions Φ. The implication is that as we increase σ^*, the risk of ending with a reserve deficit increases for any μ^*. Hence, a shock to σ^* captures greater funding risk which we characterize in the next proposition.

Proposition 2 (Funding risk shock)**.** *Consider an increase in the dollar funding risk, σ^*. Suppose that Assumption 1 holds.*

1) If the shock is i.i.d, then the shock appreciates the dollar, raises the dollar liquidity ratio, and increases the $\mathcal{DLP}$. In particular,

$$\frac{d\log e}{d\log \sigma^*} = \frac{d\log \mu^*}{d\log \sigma^*} = \frac{\mathcal{DLP}_{\sigma^*}\sigma^*}{R^b - \mathcal{DLP}_{\mu^*}\mu^*} > 0, \quad and \quad d\mathcal{DLP} = \bar{R}^{m,*}d\log e > 0.$$

2) If the shock is permanent, then the shock appreciates the dollar, raises the liquidity ratio, and the $\mathcal{DLP}$ remains constant. In particular,

$$\frac{d\log e}{d\log \sigma^*} = \frac{d\log \mu^*}{d\log \sigma^*} = -\frac{\mathcal{DLP}_{\sigma^*}\sigma^*}{\mathcal{DLP}_{\mu^*}\mu^*} \quad and \quad d\mathcal{DLP} = 0$$

Proposition 2 presents a central result. In response to a rise in the dollar funding risk, the dollar appreciates, and there is an increase in the dollar liquidity ratio and the $\mathcal{DLP}$. Intuitively, with a larger dollar funding risk, banks demand a greater amount of real dollar reserves. With the nominal supplies given, this must lead to an appreciation of the dollar. Again, there is a relevant distinction between temporary and permanent shocks. When the shock is temporary, the expected depreciation of the dollar reduces the expected real return of holding dollar reserves. Given the nominal rates, this implies that the $\mathcal{DLP}$ must be larger in equilibrium for (19) to hold. When the shock is permanent, the volatility shock

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[16]Constant returns to scale in the interbank matching technology is key for this result. As banks proportionally scale up dollar deposits and reserves, given the same real returns on dollar and euro reserves, the original liquidity ratio remains consistent with the new equilibrium.

appreciates the dollar without any effects on the $\mathcal{DLP}$. Unlike the case of the shock to the scale of dollar funding, in this case the liquidity ratio increases together with the exchange rate. In equilibrium, therefore, the increase in the liquidity ratio offsets the higher volatility, and that is why the $\mathcal{DLP}$ remains constant. The magnitude of the response is proportional to the magnitude of the response of the dollar liquidity premium to σ^*, $\mathcal{DLP}_{\sigma^*} > 0$.

Proposition 2 characterizes the effects of changes in volatility for i.i.d. or permanent shocks, and perfectly inelastic deposit supply schedules. Yet, the effects hold for mean-reverting processes and general elasticities: Based on a calibration to be described below, in Figure 3 we obtain results that fall in the middle between the i.i.d. and permanent shock. That is, we observe that a higher funding risk appreciates the dollar (panel a) and lowers the expected return on dollar bonds relative to euros (panel b), reflecting the larger dollar liquidity premium. In addition, we can see a rise in the differential rate on deposits (panel c). That is, the rate on euro deposits increases relative to the dollar rate as the rise in volatility makes euro deposits more attractive. Finally, we also see an increase in the dollar liquidity ratio that is concomitant with a reduction in the euro liquidity ratio (panel d).

Connecting the theoretical and empirical results. The empirical results in Section 2 establish a positive correlation between the strength of the dollar and the liquidity ratio. The theoretical results in Propositions 1 and 2 link funding level and funding risk shocks to the liquidity ratio and the exchange rate. The results suggest that dollar funding risk may drive a positive correlation between the liquidity ratio and the exchange rate, whereas dollar funding-level shocks predict the opposite correlation.

Toward shedding further light on the connection between the theoretical and empirical results, we generalize the results in Propositions 1 and 2 to mean-reverting shocks, under a local approximation around the steady state. Assume that the shocks follow a log AR(1) process

$$\ln (x_t) = (1 - \rho^x) \ln (x_{ss}) + \rho^x \cdot \ln (x_{t-1}) + \Sigma^x \varepsilon_t^x, \quad \text{for any } x \in \{D^*, \sigma^*\} \tag{21}$$

where ρ^x is the mean-reversion rate of x and Σ^x its standard deviation of innovations. We then have the following lemma.

Lemma 2 (Persistent shock)**.** *Consider shocks $\{D_t^*, \sigma_t^*\}$ that follow the process in* (21) *and suppose that Assumption 1 holds. Then, we have the following results about small deviations of shocks near the steady state:*

i) In response to a small deviation to D^* near the steady state:

$$\epsilon_{D^*}^e \equiv \frac{\log e - \log e_{ss}}{\log D^* - \log D^*_{ss}} \approx \frac{-\mathcal{DLP}^*_{\mu^*}\mu^*}{(1 - \rho^{D^*})R^b - \mathcal{DLP}^*_{\mu^*}\mu^*} \in (0,1)$$

and

$$\epsilon_{D^*}^{\mu^*} \equiv \frac{\log \mu^* - \log \mu^*_{ss}}{\log D^* - \log D^*_{ss}} \approx -\frac{(1 - \rho^{D^*})R^b}{(1 - \rho^{D^*})R^b - \mathcal{DLP}^*_{\mu^*}\mu^*} \in (-1,0).$$

ii) In response to a small deviation near σ^*_{ss}:

$$\epsilon_{\sigma^*}^{\mu^*} \equiv \frac{\log \mu^* - \log \mu^*_{ss}}{\log \sigma^* - \log \sigma^*_{ss}} = \epsilon_{\sigma^*}^e \equiv \frac{\log e^* - \log e^*_{ss}}{\log \sigma^* - \log \sigma^*_{ss}} \approx \frac{\mathcal{DLP}^*_{\sigma^*}d\sigma^*}{(1 - \rho^{\sigma^*}) R^b - \mathcal{DLP}^*_{\mu^*}\mu^*} > 0.$$

Using the results in Lemma 2, we now formally establish the predictions of the model for univariate regressions in the following proposition.

Proposition 3. *Consider a steady state. Then, up to a first order, the regression coefficient of the change in the exchange rate against the change in the liquidity ratio is:*

$$\beta_{\mu^*}^e = \sum_{x \in \{\sigma^*, D^*\}} \frac{\epsilon_x^e}{\epsilon_x^{\mu^*}} \cdot \boldsymbol{w}_x,$$

where

$$\frac{\epsilon_{\sigma^*}^e}{\epsilon_{\sigma^*}^{\mu^*}} = 1 \text{ and } \frac{\epsilon_{D^*}^e}{\epsilon_{D^*}^{\mu^*}} = \frac{\mathcal{DLP}^*_{\mu^*}\mu^*}{(1 - \rho^{D^*})R^b} < 0.$$

with weights given by

$$\boldsymbol{w}^{\sigma^*} = \frac{\left(\epsilon_{\sigma^*}^{\mu^*}\Sigma^{\sigma^*}\right)^2 \left(1 - (\rho^{D^*})^2\right)}{\left(\epsilon_{\sigma^*}^{\mu^*}\Sigma^{\sigma^*}\right)^2 \left(1 - (\rho^{D^*})^2\right) + \left(\epsilon_{D^*}^{\mu^*}\Sigma^{D^*}\right)^2 \left(1 - (\rho^{\sigma^*})^2\right)} = 1 - \boldsymbol{w}^{D^*}.$$

The takeaway of Proposition 3 is that the regression coefficient is a weighted average of the effects of σ^* and D^* on the correlation between the changes in the exchange rate and the liquidity ratio. In Section 2, we obtained a positive coefficient for all currencies except Japan. That Proposition 3 helps us interpret that funding-risk shocks must have been relatively more volatile and persistent than funding-level shocks. We come back to this observation after we calibrate and estimate the model.

4.3 Central Bank Policies

Nominal Rates. We now study how monetary policy affects the exchange rate. We start by considering the effect of a change in the nominal policy rates.

Proposition 4 (Effects of Changes in Policy Rates)**.** *Consider an increase in the interest rate on dollar reserves, $i^{*,m}$, holding fixed the policy spread, $i^{*,w} - i^{*,m}$.*

1) If the shock is i.i.d, the shock appreciates the dollar less than one for one, raises the liquidity ratio, and reduces the $\mathcal{DLP}$:

$$\frac{d \log e}{d \log (1 + i^{*,m})} = \frac{d \log \mu}{d \log (1 + i^{*,m})} = \frac{\bar{R}^{m,*}}{R^b - \mathcal{DLP}_{\mu^*} \cdot \mu^*} \in (0, 1) \quad and$$

$d\mathcal{DLP} = \bar{R}^{m,*} (d \log e - d \log (1 + i^{m,*})) < 0.$

2) If the shock is permanent, the shock appreciates the dollar, raises the liquidity ratio, and reduces the $\mathcal{DLP}$:

$$\frac{d \log e}{d \log (1 + i^{*,m})} = \frac{d \log \mu^*}{d \log (1 + i^{*,m})} = -\frac{\bar{R}^{m,*}}{\mathcal{DLP}_{\mu^*} \cdot \mu^*} > 0, \quad and$$

$d\mathcal{DLP} = -\bar{R}^{m,*} d \log(1 + i^{m,*}) < 0.$

Proposition 4 establishes that in response to an increase in the US nominal rate, the dollar appreciates, the liquidity ratio increases, and the liquidity premium falls. This occurs regardless of whether the shock is temporary or permanent. The appreciation of the dollar follows a standard effect: a higher nominal rate leads to a larger demand for dollars, which in equilibrium requires a dollar appreciation. In turn, given a fixed nominal supply of dollar reserves, there is an increase in the real amount of reserves. In the absence of liquidity premia, the difference in nominal returns across currencies would be exactly offset by the expected depreciation of the dollar, following the current revaluation. With a liquidity premium, however, the expected depreciation is not one for one: given the larger abundance of real dollar reserves, there is a decrease in the marginal value of dollar reserves, together with a reduction in dollar liquidity premium.

This result breaks the tight connection between interest-rate differentials and expected depreciation. In models where uncovered interest parity holds, an increase in the dollar interest rate leads to a one-for-one expected depreciation of the dollar, and no change in the expected excess return on euro reserves. Here, the exogenous increase in the dollar interest rate reduces the dollar liquidity premium, hence reducing the ex ante excess returns to euro reserves. This relationship is consistent with the well-known empirical finding known as the UIP puzzle (or Fama puzzle).[17]

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[17]For recent treatments of the UIP puzzle see Hassan and Mano (2019) and Engel (2016).

(a) Exchange Rate

(b) Real Rates on Reserves

(c) Liquidity Ratios

(d) Real Deposit Rates
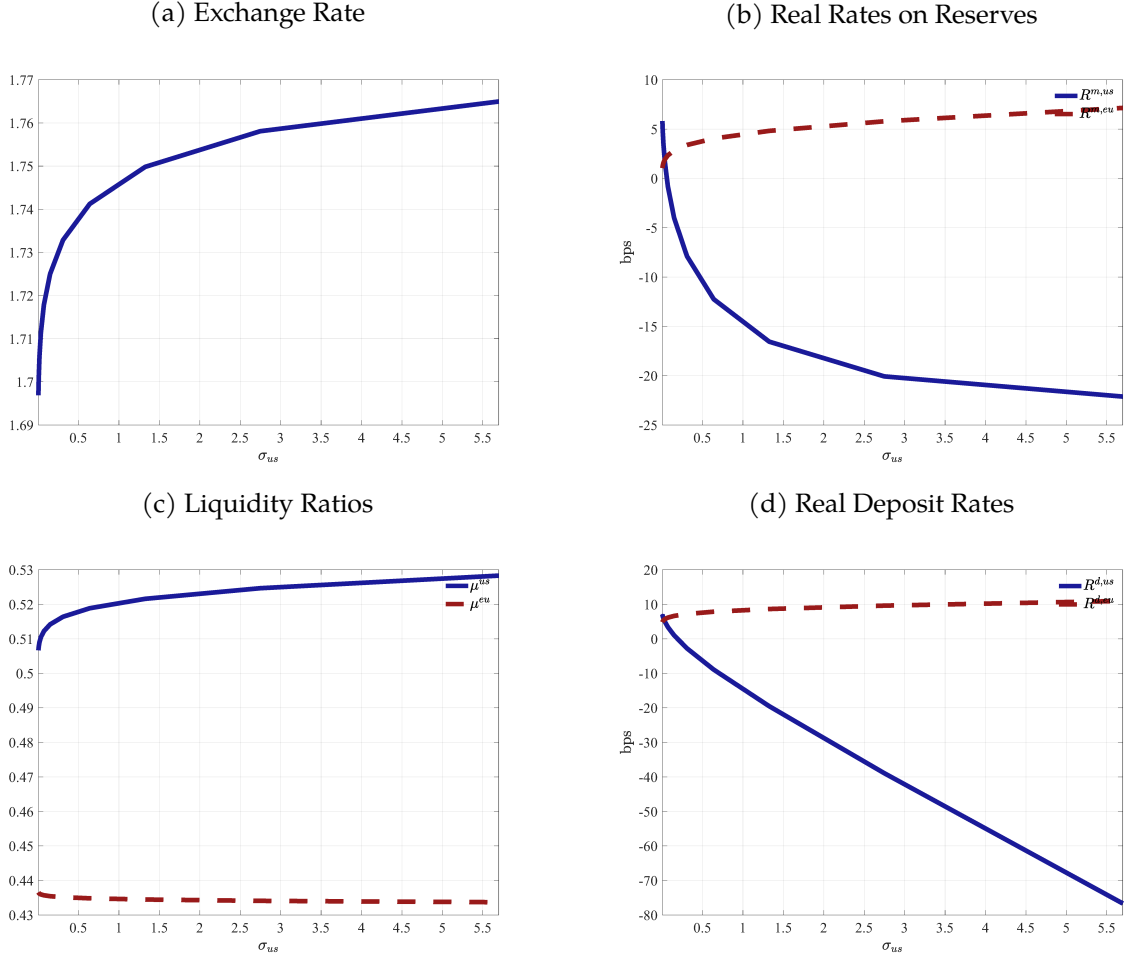
Figure 3: Equilibrium for different values of dollar funding risk

Open-Market Operations. Finally, we consider open-market operations. In the model description, expansions in M are implemented with transfers—that is, helicopter drops. In practice, central banks conduct open-market operations purchasing assets and issuing central bank liabilities. Given that we interpret M as capturing central bank and government liabilities, we are interested in unconventional open-market operations. For that, we now modify the model and assume that there is an outstanding amount of private securities S_t, some of which are held by households, S_t^h, and some of which are held by the central bank, S_t^g. We assume that these securities are perfect substitutes for private deposits. The joint demand for sum deposits and securities is given by

$$D_t + S_t^h = \Theta_t^d \left(\bar{R}_{t+1}^d \right)^{\epsilon^{d^*}}.$$

The government budget constraint is modified by adding $\left(1 + i_t^d\right) S_t^g$ to the sources of funds and S_{t+1}^g to the uses, to the right-hand side and left-hand side of (15) respectively. We have analogue conditions for dollars. Next, we characterize the effects of an open-market purchase of securities in the US.

Proposition 5 (Effects of open-market operations). *Consider a purchase of private securities financed with rserves by the central bank in the US. Let $\Upsilon^* = \frac{P^* S^{G,*}}{M^*}$ denote the initial value of the securities as a function of reserves.*

1) If the change in the balance sheet is reversed in the following period, the shock increases depreciates the dollar, raises the liquidity ratio, and reduces the $\mathcal{DLP}$:

$$\frac{d \log e}{d \log S_t^{*,g}} = \frac{\mathcal{DLP}_{\mu^*}^* \mu^* \left(1 - \mu^*\right) \mathcal{BP}^*}{R^b - \left(1 - \Upsilon^*\right) \mathcal{DLP}_{\mu^*}^* \mu^*} < 0,$$

$$\frac{d \log \mu^*}{d \log S_t^{*,g}} = \frac{R^b \Upsilon^* \left(1 - \mu^*\right)}{R^b - \left(1 - \Gamma^*\right) \mathcal{DLP}_{\mu^*}^* \mu^*} > 0, \quad \text{and} \quad d\mathcal{DLP} = \bar{R}^{m,*} d \log e < 0.$$

2) If the change in the balance sheet is permanent, the shock depreciates the dollar, and does not change the liquidity ratio nor the dollar liquidity premium:

$$\frac{d \log e}{d \log S^{*,G}} = - \left(1 - \mu^*\right) \frac{\Upsilon^*}{1 - \Upsilon^*} \leq 0.$$

Proposition 5 establishes that a temporary open market operation—by increasing the nominal supply of reserves—leads to a temporary depreciation of the dollar. Given nominal rates on reserves, the expected appreciation leads to an increase in the expected return on dollar reserves and an increase in the real holdings of dollar reserves. In equilibrium, there is there an increase in the liquidity ratio and a decrease in the $\mathcal{DLP}$. For permanent shocks, instead, we find that the exchange rate depreciates permanently and there are no effects on liquidity ratio nor the $\mathcal{DLP}$.[18]

4.4 Extensions

Dollars as Collateral. In the model, the key asymmetry needed to to deliver a positive $\mathcal{DLP}$, is that the dollar funding risk must be greater, an assumption consistent with the prevalence of the US dollar in short-term liability funding. The model, however, can be adapted to allow for an asymmetry in settlement frictions in a way that also generates a

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[18]Our model has also predictions for the effects of foreign exchange interventions, where a central bank swaps domestic liabilities for foreign assets. We leave this for future research.

positive dollar liquidity premium without differences in the dollar and euro funding risk. Specifically, assuming that banks can transfer dollar reserves to settle withdrawals of euro deposits, it follows that if banks are in deficit of euro reserves, they use dollar reserves before going to the euro interbank market. With this, the return on euro reserves must exceed the one on dollar reserves, even if the funding risks are the same in both currencies.

Risk Premia. To focus squarely on liquidity and highlight the novel channels of our theory, we have assumed risk-neutral banks. In doing so, we have abstracted from the "risk premia view" that postulates that the dollar appreciates in bad times, and as a result, episodes of high volatility, coupled with risk aversion, imply that the dollar appreciates in times of high uncertainty. Here, we extend our framework to allow for risk premia and establish a connection between risk premia and liquidity premia.

We assume that banks maximize profits using a stochastic discount factor $\Lambda(X, X')$, which captures the risk aversion of shareholders. Incorporating this feature in the portfolio problem (11), we have that

$$
\mathbb{E}\left[R_{t+1}^m - R_{t+1}^{m,*}\right] = \mathbb{E}\left[\chi_{m^*}\left(s^*; \theta^*\right) - \chi_m\left(s; \theta\right)\right]
$$
$$
+ \frac{\mathbb{COV}\left(\Lambda_{t+1}, \chi_{m^*}\left(s^*; \theta^*\right) - \chi_m\left(s; \theta\right)\right) + \mathbb{COV}\left(\Lambda_{t+1}, R_{t+1}^{m,*} - R_{t+1}^m\right)}{\mathbb{E}\left[\Lambda_{t+1}\right]}. \quad (22)
$$

Relative to (19), (22) has a risk premium associated with the liquidity premium, which is the first covariance term. In addition, there is now an additional "safety premium" term driving the difference between expected returns on the dollar and euro liquid assets. The safety premium represents the covariance between the difference in the realized yields of dollar and euro liquid assets and the stochastic discount factor. If the dollar tends to appreciate in bad times (i.e., when marginal utility is high), this implies that dollar assets will have a lower expected rate of return.

The two premia, the liquidity premium and the safety premium, interact in an important way. As explained in Proposition 2, the dollar appreciates in response to a rise in the volatility of withdrawal shocks through a higher $\mathcal{DLP}$. To the extent that the rise in the volatility of withdrawals coincides with a high value for $\Lambda(X, X')$, a volatility shock would further increase the safety premium as the return on dollar assets rises when payoffs are more valuable. Thus, modeling an endogenous liquidity premium is likely to enhance the importance of the risk premium as a driver of exchange rates, a point that may resolve the

reserve currency paradox in risk-premium models documented in Maggiori (2017).[19]

CIP Deviations. Our baseline model does not include an explicit forward market. To speak to the observed deviations from covered interest parity (CIP), we now allow for a forward market, which we assume to be perfectly competitive. A forward traded at time t promises to exchange one dollar for $\hat{e}_{t,t+1}$ euros in the lending stage in the following period.[20] The first-order condition with respect to the quantity of forwards purchased can be expressed as

$$0 = \mathbb{E}\left[\frac{\Lambda_{t+1}}{1+\pi_{t+1}} \cdot (e_{t+1} - \hat{e}_{t,t+1})\right]. \tag{23}$$

Let us examine the CIP deviation constructed using reserves. In the literature, this is often referred to as the "Treasury basis"—that is, the yield on an actual US Treasury (the analogue of reserves in our model) minus the yield on an equivalent synthetic US Treasury. Denoting by $\mathcal{CIP}$ the deviation from covered interest parity, we have that by definition

$$\mathcal{CIP} = (1 + i_t^m) - (1 + i_t^{m,*})\left(\frac{\hat{e}_{t+1}}{e_t}\right). \tag{24}$$

Replacing the forward rate $\hat{e}_{t,t+1}$ from (23) into (24) and using (22), we can obtain

$$\mathcal{CIP} = \frac{\mathbb{E}\left[\Lambda_{t+1}\left(\chi_{m^*} - \chi_m\right)\right]}{\mathbb{E}\left(\Lambda_{t+1}\left(1 + \pi_{t+1}^*\right)^{-1}\right)}. \tag{25}$$

That is, according to our model, the CIP deviation is given by the nominal risk-adjusted dollar liquidity premium. Accordingly, in the quantitative analysis, we will use the empirical time series of the CIP deviation to discipline the calibration of the model.

In addition, using (22) and (25), we obtain that the deviation from uncovered interest parity, $\mathcal{UIP}$, is given by the deviation from CIP plus the safety premium:

$$\mathcal{UIP} = \mathcal{CIP}\,\frac{\mathbb{E}\left(\frac{\Lambda_{t+1}}{1+\pi_{t+1}^*}\right)}{\mathbb{E}\left[\Lambda_{t+1}\right]} + \frac{\mathbb{COV}\left(\Lambda_{t+1}, R_{t+1}^{m,*} - R_{t+1}^m\right)}{\mathbb{E}\left[\Lambda_{t+1}\right]}.$$

That is, banks are willing to hold reserves at a lower return, either because they are a good hedge or because they provide a superior liquidity value.

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[19]Despite the prevalent view that risk premia may make the dollar a safe haven, Maggiori (2017) shows, in a standard model of financial intermediation, that the dollar tends to actually depreciate in bad times. The reason is that US households are optimally more exposed to aggregate risk and therefore face larger losses in bad times relative to those faced by the rest of the world.

[20]Notice that since there are no aggregate shocks in the balancing stage, it is equivalent to price the forward in the lending or in the balancing stage.

Empirically, deviations from UIP and CIP are well documented (see in particular Kalemli-Özcan and Varela, 2021 and Du, Tepper, and Verdelhan, 2018). Here, the wedge between the CIP and UIP deviations is due to the safety premium, but, in practice, there can be other forces, including borrowing constraints and regulatory constraints.[21]

An alternative, perhaps more common, measurement of CIP deviation is conducted using the interbank market rate (LIBOR), rather than the rate on government bonds. An interesting prediction of our model is that the two deviations from CIP are tightly linked.[22]

Finally, we highlight an interesting observation made by Du, Tepper, and Verdelhan (2018) regarding the cross-section implications of the CIP deviation. Since the global financial crisis, low-interest-rate currencies have experienced a high risk-free excess return relative to that of the high-interest-rate currencies, a pattern that contrasts sharply with the carry-trade phenomenon. As we showed earlier, a decrease in the nominal interest rate increases the $\mathcal{DLP}$ and thus raises the deviation from CIP. Our model is thus qualitatively consistent with this empirical pattern.[23]

5   Quantitative Analysis

We now explore a quantitative version of the model. We use the euro-dollar exchange rate, liquidity ratios, policy variables and observed premia to calibrate the model and estimate the shocks. We then study the importance of the dollar funding risk to account for movements in the exchange rate. We replace the $\{*\}$ notation with $i \in \{us, eu\}$ to avoid confusion as we also introduce other currencies into the analysis below.

5.1   Additional Features

Before we proceed to the description of the calibration and estimation, we modify the model to incorporate additional features that help it quantitatively account for the data.

Limited equity. In the baseline model, banks have unlimited access to equity financing. This is because banks have linear utility and face no lower bound on dividend payments. This assumption ensures that the return on loans is fixed at $1/\beta$, the return on bank equity.

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[21] In the quantitative analysis that follows, we will consider an exogenous wedge as a stand-in for these factors, using a risk-neutral version of the model. An alternative that we leave for future research is to take an explicit stochastic discount factor.

[22] In particular, we can show that under risk neutrality, the difference between the interbank market-based CIP and the government bond-based CIP depends on the endogenous liquidity objects and is given by $\chi_t^+/\Psi_t^+ - \chi_t^{+,*}/\Psi_t^{+,*}$.

[23] An alternative explanation provided by Amador, Bianchi, Bocola, and Perri (2020) highlights central bank policies of resisting an appreciation at the zero lower bound. In their framework, deviations from CIP arise when a central bank purchases foreign reserves and the bank's financial constraint prevents an arbitrage between domestic and foreign assets.

This simplifies the analytical characterization above. However, the assumption is unrealistic because all the movements in the bond premium, $\mathcal{BP}$, follow from changes in the real expected return to dollar reserves, but not on the loan rate. To enrich the quantitative model and deliver endogenous variations in the loan rate, we assume that banks face limited equity financing. Specifically, we assume that banks do not accumulate equity: they pay out their realized previous-period profits as dividends (or raise equity to finance their losses). Since average profits must equal zero in equilibrium, this implies that averaging across banks, reserves and loans must be financed with deposits:

$$\tilde{b}_t + \tilde{m}_t^{us} + \tilde{m}_t^{eu} = \tilde{d}_t^{us} + \tilde{d}_t^{eu}. \tag{26}$$

Based on this equity funding friction, the loan rate is no longer fixed. Aside from this feature, the bank problem is the same.

Open-market operations. Since unconventional open-market operations have been prevalent since the 2008 crisis, we assume that all deviations in the money supply away from the steady state are due to increases in the stock of securities. Thus we have that $M_t^{us} - M_{ss}^{us} = S_t^{g,us}$, where S_t^{us} is the security holdings of the Federal Reserve, as described in Section 4.3. We use analogous equations for the euro.

CIP-UIP wedge. In the data, the deviation from UIP exceeds by some margin the deviations from CIP (see, e.g., Kalemli-Özcan and Varela 2021). In our baseline model with risk neutrality, UIP and CIP coincide. We also showed in Section 4.4 that the model can be extended to allow for risk premia to account for that wedge. In what follows, we leave open an explicit interpretation and use a simple "risk-premium wedge," denoted by ξ_t, to express the difference between the UIP and CIP deviations, $\mathcal{UIP}_t = \mathcal{CIP}_t + \xi_t$.

5.2   Calibration and Estimation

We calibrate externally and internally a subset of parameters and estimate the autocorrelation and variances of different shocks to the model. For the distributions of the payment shocks, Φ, we adopt a parametric form: We assume the Φ in each country is a two-sided exponential distributionindexed by a σ volatility parameter.[24] Each possible distribution is indexed by a single dispersion parameter, σ, and the distribution is centered at zero.

Shock processes. We deduce shocks to the payment volatility, funding and the risk-premium wedge. In particular, at each date, there are distributions of payment shocks to dollar and

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[24]This distribution is convenient because it allows for a continuum of shocks but renders closed form solutions for the conditional expectations below a threshold, allowing us to compute the reserve deficit probability analytically, which is useful in computations.

euros, σ_t^i for $i \in \{us, eu\}$, the scale of deposits $\Theta_t^{d,i}$ for $i \in \{us, eu\}$, and the wedge in the UIP condition, ξ_t. In addition, we assume that there are shocks to the interest on reserves, $i_t^{m,i}$, and to the money supply, M_t^i, which follow a log AR(1) process in (21) for $X \in \left\{\xi_t, \sigma^i, \Theta^{d,i}, i^{m,i}, M_t^i\right\}_{i \in \{us, eu\}}$. Overall, we have 9 shocks and 18 parameters.

From the model's perspective, $\left\{i_t^{m,i}, M_t^i\right\}_{i \in \{us, eu\}}$ are policy variables that have observable counterparts, so their processes can be directly estimated using (21). By contrast, $\left\{\xi_t, \sigma_t^{us}, \Theta_t^{d,us}, \sigma_t^{eu}, \Theta_t^{d,eu}\right\}$ are unobservables that we deduce these using the Kalman filter and whose persistence and variance parameters we estimate. Thus, we have a total of four observable policy variables, $\left\{i_t^{m,i}, M_t^i\right\}_{i \in \{us, eu\}}$, and five unobservable shocks, $\left\{\xi_t, \sigma_t^{us}, \Theta_t^{d,us}, \sigma_t^{eu}, \Theta_t^{d,eu}\right\}$.

Data counterparts. We use monthly data from 2001m1 to 2016m12. The data series employed as counterparts are presented in Figure 8. We use the three-month US and German government bond rate as the data counterparts for $i_t^{m,us}$ and $i_t^{m,eu}$—see panels (c) and (d). In the model, the exchange rate is stationary, whereas the data feature a slight inflation differential. Since the model is stationary, we divide each bond rate by the average annual inflation in the corresponding area of the sample, in order to construct an $i_t^{m,i}$ net of inflation. For the counterpart of money supply M_t^{us}, we use the one we used in Section 2. For the data counterpart of M_t^{eu} we use the sum of holdings of Euro Area Government Issued securities and Cash held by Monetary Financial Institutions (MFI). With this data $\left\{i_t^{m,i}, M_t^i\right\}_{i \in \{us, eu\}}$, we estimate $i_{ss}^{m,i}$, $\rho^{i^{m,i}}$, and $\Sigma^{i^{m,i}}$ for $i \in \{us, eu\}$. The estimates are found in Table B1.

To obtain the filtered time series for the unobservables $\left\{\xi_t, \sigma_t^{us}, \Theta_t^{d,us}, \sigma_t^{eu}, \Theta_t^{d,eu}\right\}$, we use data counterparts for $\{\mathcal{CIP}, \mathcal{BP}^*, \mu, \mu^*, e\}$ which are equilibrium objects in the model. For the data counterpart of $\mathcal{CIP}$, we use the mid-point quotes for spot and forward exchange rates from Bloomberg and the nominal rates on the rates on reserves as data counterparts of the terms in equation (19). For the reference period, we obtain a value of 12 basis points, in line with Du, Tepper, and Verdelhan (2018). For the data counterpart of $\mathcal{BP}^*$, we use a measure of liquidity proposed by Stock and Watson (1989) and Friedman and Kuttner (1993), the commercial paper spread, and the difference between the three-month spread between the AAA commercial paper and the three-month Treasury bill, our analogue for the policy rate.

The data counterpart of μ^* is the series used in Section 2. We construct an analogous series for the euro area, μ by dividing M^{eu} by all deposits redeemable at notice and deposits with agreed maturity held by (MFI). As we noted in Figure 1, the liquidity ratio for the US may be greater than one, because we us the liquid assets holdings of a broader class of institutions, but only the deposit stock of the banking system. For the regressions, this does

not matter, since we conduct the regression in changes. Here, we scale the liquidity ratio so that the steady-state targets for μ^{us} and μ^{eu} are about 0.2, a figure consistent with the data targets in Bianchi and Bigio (2021) which are, in turn, taken from bank call reports. The scaled liquidity ratios are plotted in panel (b) in Figure 8 in the Appendix.

External calibration. We set the matching efficiency parameters of the matching process, the penalty rate i^w, and the bargaining powers, embedded in (5), to the values from Bianchi and Bigio (2021).[25] We do the same for the values for the semi-elasticities of the loan demand and deposit supply schedules, treating the euro area and the US funding supplies as symmetric. It is worth noting that penalty rate i^w is does not correspond to the discount window rate set by central banks. Rather, we interpret this penalty more broadly as capturing stigma or the cost of collateral. Following the estimation in Bianchi and Bigio (2021), we set this value to 10% annually. The loan demand scale Θ^b is set to one as a normalization. The parameters values are listed in Table B1.

Internal calibration. We next describe the parameterization of the steady-state values of the shock processes $\{\sigma_{ss}^{us}, \sigma_{ss}^{eu}, \xi_{ss}, \Theta_{ss}^{d,us}, \Theta_{ss}^{d,eu}\}$, which are set to match data targets. We assume symmetry in the funding scales at steady state, $\Theta_{ss}^{d,us} = \Theta_{ss}^{d,eu}$. We are thus left with four parameters to match four moments. Without loss of generality, we assume an economy with zero steady state inflation and adjust all nominal rates to deliver the real rates observed in the data. That is, we set $\{\bar{R}_{ss}^{m,us}, \bar{R}_{ss}^{m,eu}\} = \{1 + i_{ss}^{m,us}, 1 + i_{ss}^{m,eu}\}$. The values of M_{ss}^{eu} and M_{ss}^{us} can be normalized. For simplicity, we set M_{ss}^{eu} to obtain a price in euros equal to one and M_{ss}^{us} to generate exchange rate level of the data using (16). In this step, we calibrate the steady-state values to the time-series averages between the years 2002 and 2005, rather than estimating these parameters, because the 2002:2005 period was relatively stable.

We adopt a sequential procedure to calibrate the steady state parameters. First, we solve for σ_{ss}^{us} from $\mathcal{BP}_{ss}^* = \mathbb{E}\left[\chi_m\left(\mu_{ss}^{us}, \sigma_{ss}^{us}\right)\right]$. Second, we use the steady-state version of equation (24) to compute the CIP deviation and obtain σ_{ss}^{eu}. That is, $\mathcal{CIP}_{ss} = \mathbb{E}\left[\chi_m\left(\mu_{ss}^{eu}, \sigma^{eu}\right)\right] - \mathbb{E}\left[\chi_m\left(\mu_{ss}^{us}, \sigma_{ss}^{us}\right)\right]$.[26] Third, the average risk-premium, ξ_{ss}, is obtained from $\mathcal{UIP}_{ss} = \mathcal{CIP}_{ss} + \xi_{ss}$, where we use $\mathcal{UIP}_{ss} = R_{ss}^m - R_{ss}^{m,*}$ as a data analogue.[27] Finally, we obtain $\Theta_{ss}^{d,us}$ from

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[25]See Appendix C for the mapping between the efficiency parameter λ and bargaining powers η to the probabilities of matching and the interbank market rate.

[26]Note that to reconcile an average $\mathcal{BP}_{ss} > \mathcal{CIP}_{ss}$, the calibration calls for more volatile payments in dollars: σ_{ss}^{us} is almost four times the σ_{ss}^{eu} in steady state. This is consistent with our notion that the volatility of dollar flows is larger because of the more ample use in the short-term funding market.

[27]Kalemli-Özcan and Varela (2021) provide a comprehensive comparative analysis of the different ways to measure $\mathcal{UIP}$.

the bank's budget constraint and the target for the liquidity ratio.[28]

Filtering. Once we set the steady-state parameter values, we use a Kalman filter on the linearized version of the model to filter the unobserved shocks and estimate their persistence and variance using Bayesian maximum likelihood. As we showed in Proposition 3, these parameters govern the regression coefficients in Section 2—hence we tie our hands in terms of the ability to match those regressions.

It is instructive to discuss which data series are informative about which inferred series in the filtering step. First, as in the steady state calibration, the bond premium is informative about the payments volatility σ_t^{us}, given that $\mathcal{BP}_t^* = \mathbb{E}\left[\chi_m\left(\mu_t^{us}, \sigma^{us}\right)\right]$. Likewise, the CIP deviation is informative about σ_t^{eu}, since $\mathcal{CIP}_t = \mathbb{E}\left[\chi_m\left(\mu_t^{eu}, \sigma_t^{eu}\right)\right] - \mathcal{BP}_t$. Within a transition, the values of $\{\rho^x\}$ and the internal structure lead to a forecast of the expected future exchange rate, $\mathbb{E}\left[e_{t+1}|\xi_t, \sigma_t^{us}, \Theta_t^{d,us}, \sigma_t^{eu}, \Theta_t^{d,eu}\right]$. Thus, given the policy rates, the observed exchange rate is informative about the risk premium, ξ_t, given observed UIP and CIP deviations. Finally, the liquidity ratios are informative about $\left\{\Theta_t^{d,us}, \Theta_t^{d,eu}\right\}$ in line with the results from Proposition 1. Given the set of observables and deduced shocks, the budget constraint and the deposit demand schedules leaves two unknowns, $\left\{\Theta_t^{d,us}, \Theta_t^{d,eu}\right\}$, to match the corresponding liquidity ratios. The priors and posteriors are reported in Table B.

5.3 Quantitative Results

Model validation. Using the parameter estimates, we conduct Monte Carlo simulations (we simulate the model for 100,000 periods) to generate model moments and compare these with their data counterparts. Table B3 shows that, as expected, the model matches closely the targeted steady-state moments. In terms of untargeted moments, the model delivers a persistence and standard deviation of the exchange rate in line with the data.

An important validation our model is to test its ability to replicate the empirical analysis of Section 2 with the simulated data. To do so, we extend the analysis to multiple currencies by assuming that the funding scale of all currencies except for the euro and the dollar have measure zero in the banks' portfolio. While the funding scale is zero in all other currencies, still their liquidity ratio is pinned down by equilibrium conditions. Because deposit holdings in other currencies are infinitesimal, the equilibrium allocations do not change. However, we can also compute the exchange rates and rates of return for all other currencies: For other currencies, we assume that all shocks are the same as for the euro,

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[28]We can obtain $b = \Theta^b(R_{ss}^{m,us} + \mathcal{BP}_{ss})^{-\epsilon^b}$ from loan market clearing. Similarly, we obtain d_{ss}^{us} and d_{ss}^{eu} from their corresponding clearing conditions. Setting $\Theta_{ss}^{d,us} = \Theta_{ss}^{d,eu}$, and substituting $\{b_{ss}, d_{ss}^{us}, d_{ss}^{eu}, \mu_{ss}^{us}, \mu_{ss}^{eu}\}$ into the bank's budget constraint, (26), we obtain a single equation for $\Theta_{ss}^{d,us}$.

with the exception of the corresponding nominal policy rates, which we feed directly from the data.

With our baseline parameterization, we split the simulated series into subsamples of 234 periods (which corresponds to the length of the data sample). We report the average and standard deviation of the regression coefficients from each subsample. Table 6 shows the results of the simulated regressions. The key takeaway is that the simulated data-based regression delivers a positive coefficient and of similar scale on the liquidity ratio, just as the one we found in the data for all currencies, with the exception of the Japanese yen, which displays a negative coefficient in the empirical analysis[29]Note that the sign on the inflation variable in this table is opposite to the one estimated in the data. That arises because we have modeled monetary policy as a money-growth rule, but in the data, central banks have followed an inflation-targeting rule. Under standard stationarity conditions, an increase in inflation under an inflation-targeting rule leads to a currency appreciation, while under a money growth rule inflation is associated with depreciation. It is not the aim of this paper to model how monetary policy affects the exchange rate, and our results regarding the relationship of liquidity shocks to exchange rates are not affected by the model of the monetary policy rule.

As discussed in Proposition 3, the persistence and variance parameters of the shocks govern the regression coefficient on the liquidity ratio. We note that these parameters were estimated using the Kalman filter and were not calibrated to match the regressions coefficients. Thus, this exercise reveals that the model can match important regularities that are not targeted in the calibration.

Shock estimates. The shocks that we infer from the filtering are presented in Figure 4. From panel (a), we observe that the dollar funding risk σ_t^{us} is close to steady state before 2007 but increases sharply during the financial crisis and remains higher past that period. As Figure 8 shows, the US bond premium $\mathcal{BP}^*$ spikes during the financial crisis, while the US liquidity ratio μ_t^{us} remains consistently high after the financial crisis. To reconcile a higher liquidity ratio with a $\mathcal{BP}^*$ that returns close to steady state, the model needs a persistently high dollar funding risk, σ_t^{us}. We note that the persistent rise of σ_t^{us} after the crisis can be attributed to several factors, including the increase in counterparty risk as well as the increase in liquidity regulation, which included the liquidity coverage ratio and the net stable funding ratio (Copeland, Duffie, and Yang, 2021).

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[29]The different sign in the regression for Japan could be related to its own safe haven status. For example, it could be that yen funding is subject to larger shocks, which Proposition 3 suggests could generate a negative value. The case of Japan deserves further study and is an interesting avenue for future research.

Table 6: Regression Coefficients with Simulated Data for Multiple Currencies

	Eur	AUS	CAN	JPN	NZ	NWY	SWE	SWZ	UK
$\Delta(\text{LiqRatio}_t)$	0.135	0.172	0.179	0.179	0.174	0.165	0.172	0.178	0.175
	(0.065)	(0.113)	(0.058)	(0.059)	(0.083)	(0.062)	(0.074)	(0.059)	(0.067)
$\Delta(\pi_t^i - \pi_t^{us})$	0.207	0.238	0.196	0.196	0.226	0.201	0.217	0.196	0.211
	(0.121)	(0.193)	(0.109)	(0.111)	(0.146)	(0.112)	(0.135)	(0.111)	(0.125)
LiqRatio(−1)	0.007	0.010	0.008	0.008	0.009	0.008	0.008	0.008	0.008
	(0.023)	(0.036)	(0.021)	(0.021)	(0.028)	(0.022)	(0.026)	(0.021)	(0.024)
Constant	0.010	0.015	0.012	0.012	0.013	0.012	0.013	0.012	0.012
	(0.035)	(0.054)	(0.032)	(0.032)	(0.043)	(0.034)	(0.039)	(0.032)	(0.037)
N	234	234	234	234	234	234	234	234	234
adj. R^2	0.046	0.029	0.067	0.066	0.043	0.058	0.049	0.067	0.056

Notes: standard deviation in parenthesis. We consider 4273 sample simulations.

Panel (b) presents the euro funding risk σ_t^{eu}. As the figure shows, it is substantially lower and more stable compared with the dollar funding risk. There are a couple of dips and reversals around 2008 and the 2012 European debt crisis, which the estimation infers from fluctuations in the CIP deviations. Panels (c) and (d) show the path of the scale of dollar and euro funding. The two variables exhibit relatively lower frequency movements. For the dollar, we see a secular decline up to 2008 and a subsequent increase. For euros, we see an increase up to the 2012 crisis and then a decrease. The risk premium wedge presented in panel (e) shows a sizable negative value early 2000, which could be attributed to uncertainty and the difficulties in forecasting the exchange rate after the inception of the euro. This negative value captures that the euro was stronger than predicted from (19). After that initial transition, we see that the wedge fluctuates around zero with some spikes around 2008 and 2012.

How important is the dollar funding risk? We now investigate the extent to which the funding risk plays a role in driving exchange rate fluctuations and liquidity premia.

We present first a variance decomposition of the linearized version of the model. The results are presented in Figure 5. Each panel reports the percent contribution of each exogenous variable to a variable of interest. The figure shows that the contribution of dollar funding risk accounts for 14% of the variance of the euro-dollar exchange rate (panel a), 88% of the variance of the dollar bond premium (panel b) and 66% of the variance of CIP (panel c).
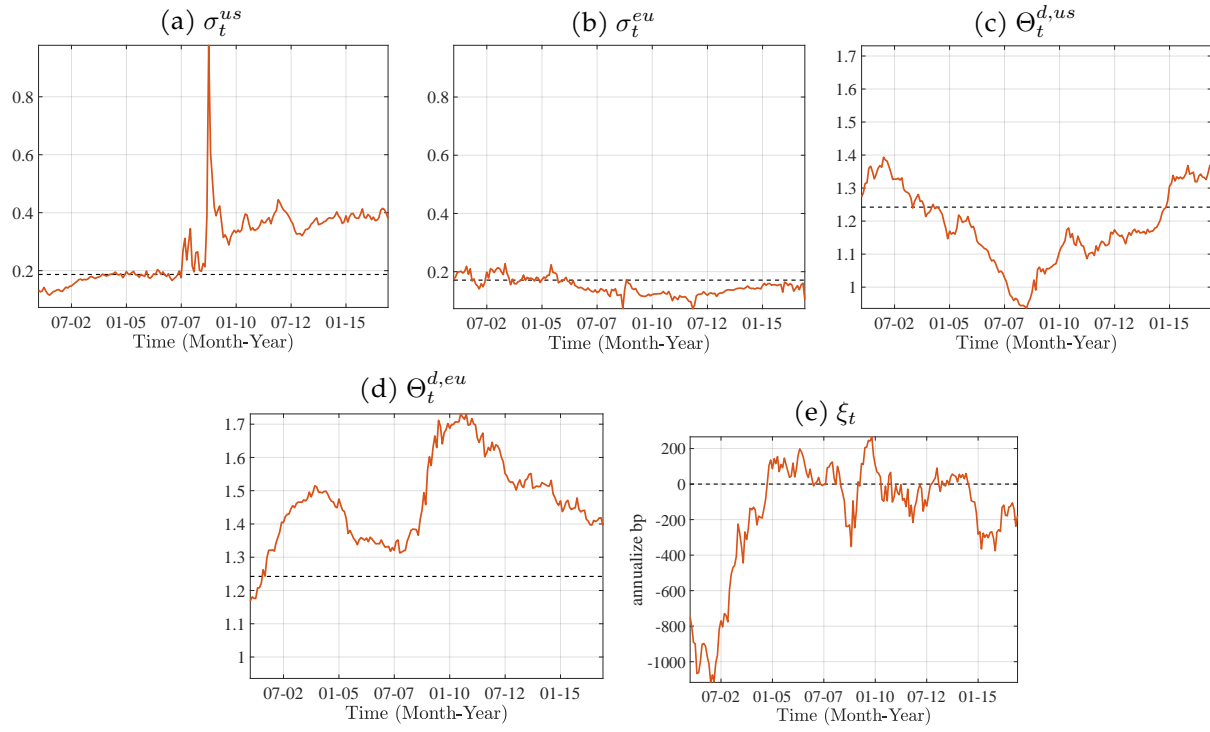
Figure 4: Estimated Shocks using the Kalman filter
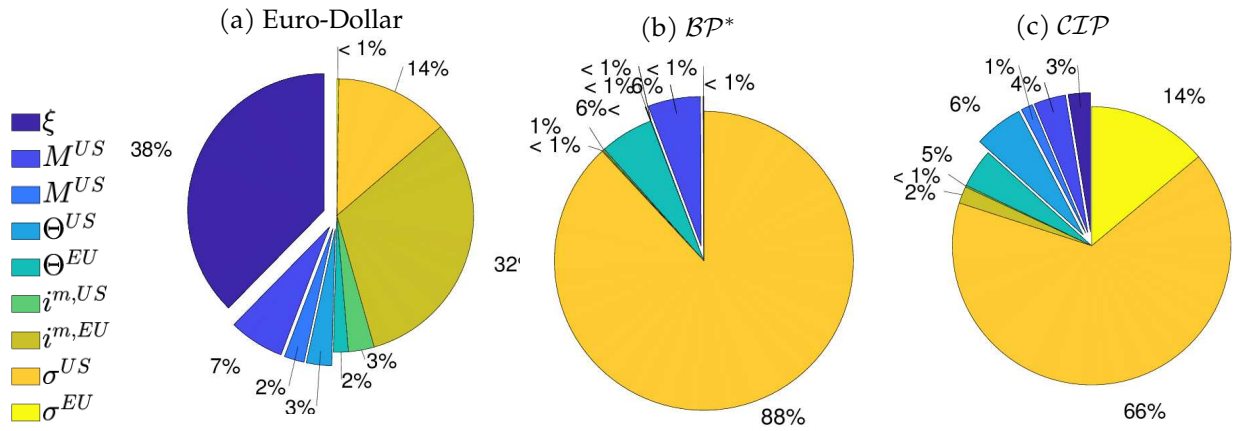
Figure 5: Variance Decomposition of Shocks
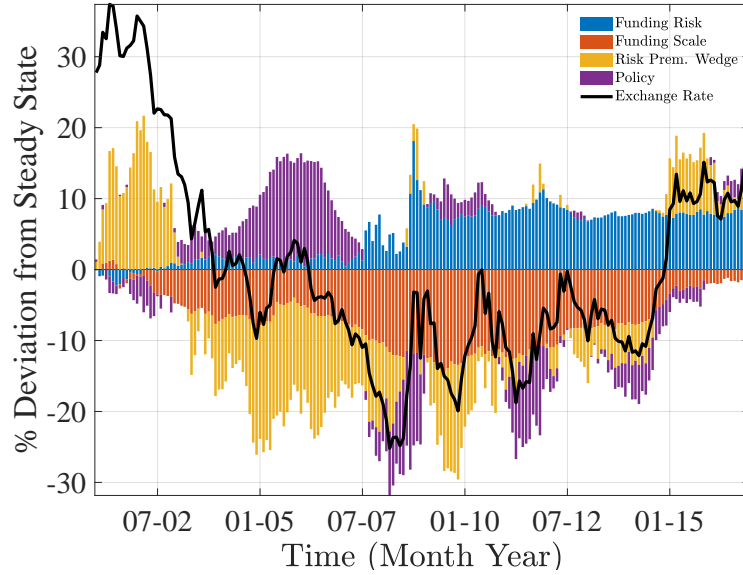
Figure 6: Shock Decomposition

Note: The figure reports the contribution of different groups of shocks in explaining the exchange rate.

Next, we analyze the contribution of the different shocks in explaining the euro-dollar the exchange rate. Figure 6 presents the results. The solid curve is the percentage deviation of the euro-dollar exchange rate from the steady state. The vertical bars are the contribution of each shock. We group together the funding risk shocks to dollars and euros, the funding level shocks to dollars and euros, the policy shocks (changes in rates and the supply of reserves) and the risk premium wedge. To compute the contribution of each shock, we turn off the shock in each period by setting the value equal to the steady state and keeping the rest of the shocks on. A key takeaway is that since the 2008 financial crisis, funding risk has played a prominent role in accounting for a stronger dollar.

To zoom in on the the role of funding risk, in Figure 7, we present the time series of the exchange rate and the CIP deviation without the funding risk shock. Consistent with the analysis, the counterfactual shows a much lower deviation from CIP (using both interest rates on reserves and interbank market rates, as explained in Section 4.4) and a more depreciated dollar.
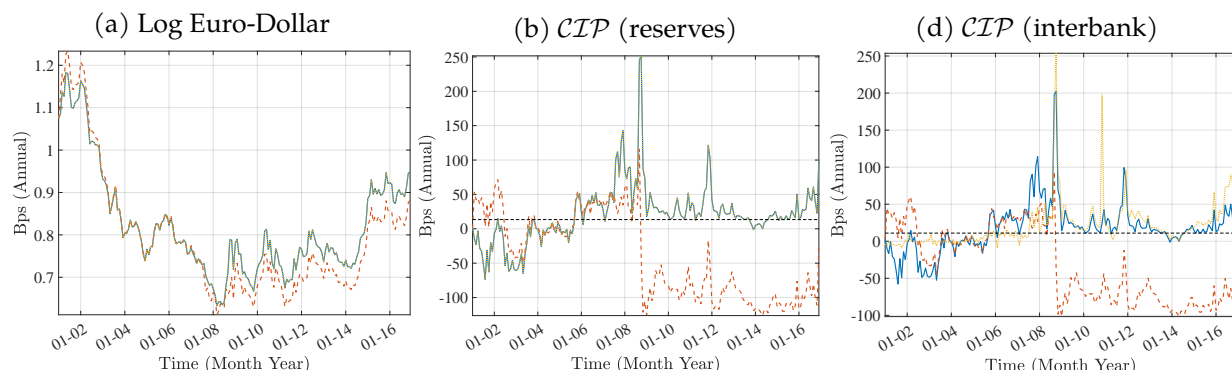
Figure 7: Counterfactual without σ^{us}

Note: The figure reports the predicted series of the model with all shocks and a counterfactual without σ_t^{us}.

The March 2020 "Dash for Cash." We argued that the model needs a persistently high dollar funding risk after 2008, to explain the strength of the dollar given the large increase in the dollar liquidity ratio. We now turn to some anecdotal evidence. A revealing case study of liquidity demand for dollars is the sudden turmoil in markets at the onset of the COVID crisis in March 2020, often referred to as the "dash for cash." As governments began to institute lockdowns in late February and the severity of the COVID crisis began to come into focus in early March, there was naturally a "flight to safety" as investors fled from equities and other risky assets into safer government-backed securities.

However, the nature of the financial stress quickly changed character, as agents turned even from assets normally considered to be safe, such as longer-term US Treasury bonds, to cash and other very liquid assets, such as Treasury bills. Even though the Fed cut rates on March 3, medium- and long-term Treasury rates began to rise on March 13th, as shown in Table B4. Yields on all bonds with maturities of five years or longer rose substantially through March 18th.

At the same time, interest rates on the shorter end of the spectrum, such as those for highly liquid Treasury bills, fell during this time period. Table B4 clearly shows this drop for maturities less than one year.

Very late on March 18th, the Federal Reserve announced a plan for dealing with the problem. It offered to buy illiquid bonds held by money market funds. This action slowed the dash toward cash, but the markets were not calmed until early in the morning of March 23rd, when the Fed announced a plan to buy large amounts of Treasury bonds and agency securities. After that move, the flight toward liquidity slowed, and the increase in long term bond rates ceased.

Consistent with the theory, Figure 9 shows the behavior of the dollar/euro exchange

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rate during this period. The dollar sharply appreciated between March 9th and March 19th, during the strongest surge of liquidity demand. The dollar subsequently began to depreciate after the Fed announced its moves to ease the liquidity shortage. Cesa-Bianchi and Eguren-Martin (2021) undertakes a detailed analysis of this episode that is completely consistent with this description. They find that the "dash for cash" was mostly a "dash for dollars" rather than liquid government bonds denominated in other currencies, which they attribute to the global demand for lqiuid dollar assets.

6 Conclusions

We develop a theory of exchange rate determination emerging from financial institutions' demand for liquid dollar assets. Periods of increased funding volatility generate a "scrambling for dollars" that raises liquidity premia and appreciates the dollar. In line with the theory, we document that a higher liquidity ratio in the financial system is associated with a stronger dollar. We also use the model as a quantitative laboratory to decompose the different forces driving exchange rate fluctuations. We conclude from our analysis that funding risk is a key factor driving fluctuations in exchange rates.

Our framework can be extended in several directions. For example, it would be interesting to allow for a richer production structure to analyze conventional channels of monetary policy. In addition, our model could be a suitable laboratory to study foreign exchange interventions, swap lines, and other less conventional policies. We leave this for future research.

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Online Appendix

A Additional Tables Empirical Analysis

Table A1: Exchange Rates and Liquidity Ratio Feb. 2001 – July 2020

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat}_t)$	0.220***	0.233***	0.148**	-0.141***	0.277***	0.184***	0.215***	0.140**	0.163***
	(4.422)	(3.359)	(2.557)	(-2.830)	(3.947)	(2.914)	(3.561)	(2.557)	(3.254)
$\pi_t - \pi_t^*$	-0.546***	-0.408**	-0.653***	0.050	-0.729***	-0.118	-0.504**	-0.649***	-0.394**
	(-3.750)	(-2.136)	(-2.656)	(0.343)	(-3.815)	(-0.807)	(-2.528)	(-2.737)	(-2.129)
$\Delta(i_t - i_t^*)$	-1.284	-0.491	-0.093	-1.793**	-1.114	-0.513	0.249	-1.541*	-0.269
	(-1.486)	(-0.599)	(-0.083)	(-2.336)	(-1.245)	(-0.638)	(0.311)	(-1.663)	(-0.351)
LiqRat_{t-1}	0.010**	0.006	0.002	-0.001	0.008	0.010	0.006	0.004	0.009*
	(2.141)	(0.940)	(0.319)	(-0.142)	(1.279)	(1.643)	(1.181)	(0.775)	(1.705)
Constant	-0.011***	-0.004	-0.007*	0.002	-0.008*	-0.006	-0.009**	-0.016***	-0.005
	(-3.239)	(-0.950)	(-1.912)	(0.349)	(-1.892)	(-1.560)	(-2.081)	(-2.980)	(-1.571)
N	234	232	148	234	232	234	234	234	234
adj. R^2	0.11	0.05	0.05	0.05	0.10	0.03	0.05	0.05	0.04

t statistics in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A2: Exchange Rates and Liquidity Ratio with VIX Feb. 2001 – July 2020

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat}_t)$	0.192***	0.155**	0.073	-0.123**	0.208***	0.137**	0.174***	0.126**	0.138***
	(3.922)	(2.592)	(1.378)	(-2.477)	(3.230)	(2.291)	(3.012)	(2.291)	(2.769)
$\pi_t - \pi_t^*$	-0.432***	-0.174	-0.421*	0.027	-0.530***	-0.033	-0.419**	-0.589**	-0.308*
	(-2.989)	(-1.054)	(-1.893)	(0.191)	(-3.016)	(-0.240)	(-2.210)	(-2.468)	(-1.676)
ΔVIX_t	0.001***	0.004***	0.003***	-0.001**	0.003***	0.002***	0.002***	0.001*	0.001***
	(3.794)	(9.317)	(6.169)	(-2.538)	(7.018)	(5.896)	(5.133)	(1.683)	(3.110)
$\Delta(i_t - i_t^*)$	-1.075	-0.404	0.456	-1.994***	-1.404*	-0.289	0.096	-1.285	-0.266
	(-1.277)	(-0.578)	(0.455)	(-2.615)	(-1.725)	(-0.385)	(0.126)	(-1.374)	(-0.353)
LiqRat_{t-1}	0.010**	0.007	0.004	-0.001	0.008	0.010*	0.007	0.004	0.008
	(2.240)	(1.299)	(0.686)	(-0.177)	(1.390)	(1.808)	(1.385)	(0.871)	(1.587)
_cons	-0.011***	-0.005	-0.006*	0.002	-0.008*	-0.006	-0.009**	-0.015***	-0.005
	(-3.095)	(-1.399)	(-1.881)	(0.291)	(-1.941)	(-1.648)	(-2.095)	(-2.837)	(-1.433)
N	234	232	148	234	232	234	234	234	234
adj. R^2	0.16	0.31	0.25	0.07	0.26	0.15	0.15	0.05	0.07

t statistics in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A3: Exchange Rates and Liquidity Ratio Instrumental Variable Regression:
$\Delta(\text{VIX})$, StDev(Inf) and StDev(XRate) instrument for $\Delta(\text{LiquidityRatio})$ Feb. 2001 – July 2021

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat}_t)$	0.641***	1.122***	0.721***	-0.388***	0.923***	0.839***	0.717***	0.138	0.801***
	(4.427)	(5.024)	(4.634)	(-3.022)	(4.599)	(4.209)	(4.094)	(0.987)	(4.315)
$\pi_t - \pi_t^*$	-1.167***	-1.276***	-0.800***	0.121	-1.102***	-0.467**	-0.763***	-0.562**	-1.035***
	(-4.481)	(-3.883)	(-2.835)	(0.811)	(-3.896)	(-2.328)	(-3.280)	(-2.250)	(-3.502)
LiqRat_{t-1}	0.014**	0.016*	0.017***	-0.004	0.012*	0.023***	0.013**	0.005	0.026***
	(2.589)	(1.958)	(2.707)	(-0.643)	(1.657)	(2.876)	(1.992)	(0.917)	(3.178)
Constant	-0.016***	-0.010*	-0.015***	0.006	-0.012**	-0.017***	-0.016***	-0.015**	-0.019***
	(-3.815)	(-1.657)	(-3.097)	(0.866)	(-2.160)	(-2.859)	(-2.979)	(-2.415)	(-3.189)
N	246	246	246	246	246	246	246	246	246

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat2}_t)$	0.098***	0.109***	0.069***	-0.012	0.123***	0.101***	0.088***	0.079***	0.103***
	(3.718)	(3.073)	(2.675)	(-0.450)	(3.388)	(3.100)	(2.789)	(2.768)	(4.049)
$\pi_t - \pi_t^*$	-0.511***	-0.406**	-0.421*	-0.082	-0.673***	-0.126	-0.440**	-0.640***	-0.346**
	(-3.480)	(-2.135)	(-1.944)	(-0.540)	(-3.519)	(-0.849)	(-2.253)	(-2.731)	(-2.065)
LiqRat2_{t-1}	0.006**	0.005	0.005*	0.004	0.005	0.006*	0.004	0.003	0.004
	(2.118)	(1.415)	(1.833)	(1.217)	(1.388)	(1.796)	(1.377)	(1.129)	(1.280)
Constant	-0.006***	-0.001	-0.002	-0.002	-0.003	-0.001	-0.005*	-0.014***	-0.001
	(-2.699)	(-0.257)	(-1.249)	(-0.659)	(-1.414)	(-0.496)	(-1.765)	(-3.175)	(-0.311)
N	234	232	234	234	232	234	234	234	234
adj. R^2	0.09	0.04	0.04	-0.00	0.07	0.04	0.04	0.04	0.06

t statistics in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A5: Exchange Rates and Alternative Measure of Liquidity Ratio with VIX

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat2}_t)$	0.090***	0.088***	0.059**	-0.008	0.106***	0.088***	0.078***	0.074***	0.096***
	(3.501)	(2.933)	(2.544)	(-0.283)	(3.233)	(2.911)	(2.625)	(2.616)	(3.833)
$\pi_t - \pi_t^*$	-0.393***	-0.188	-0.299	-0.112	-0.480***	-0.052	-0.379**	-0.575**	-0.274*
	(-2.721)	(-1.163)	(-1.543)	(-0.742)	(-2.748)	(-0.373)	(-2.052)	(-2.451)	(-1.655)
ΔVIX_t	0.001***	0.004***	0.002***	-0.001**	0.003***	0.002***	0.002***	0.001**	0.001***
	(4.215)	(9.677)	(7.735)	(-2.589)	(7.238)	(6.145)	(5.446)	(2.126)	(3.330)
LiqRat2_{t-1}	0.006**	0.006*	0.005**	0.004	0.006*	0.007*	0.005*	0.003	0.003
	(2.224)	(1.860)	(2.137)	(1.259)	(1.656)	(1.951)	(1.663)	(1.220)	(1.268)
Constant	-0.005**	-0.001	-0.002	-0.003	-0.003	-0.001	-0.004*	-0.013***	-0.000
	(-2.372)	(-0.660)	(-1.235)	(-0.829)	(-1.466)	(-0.502)	(-1.698)	(-2.931)	(-0.277)
N	234	232	234	234	232	234	234	234	234
adj. R^2	0.15	0.32	0.23	0.02	0.24	0.17	0.15	0.06	0.10

t statistics in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A6: Exchange Rates and Alternative Measure of Liquidity Ratio Instrumental Variable Regression: Δ(VIX), StDev(Inf) and StDev(XRate) instrument for Δ(LiqRat2)

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz
Δ(LiqRat2$_t$)	0.471***	0.822***	0.484***	-0.296**	0.651***	0.649***	0.507***	0.105
	(3.276)	(3.327)	(3.420)	(-2.251)	(3.250)	(3.135)	(3.076)	(0.882)
$\pi_t - \pi_t^*$	-0.774***	-1.007***	-0.552*	0.171	-1.023***	-0.527**	-0.678**	-0.677**
	(-3.466)	(-2.679)	(-1.734)	(0.788)	(-3.468)	(-1.978)	(-2.466)	(-2.353)
LiqRat2$_{t-1}$	0.008**	0.010	0.008*	-0.001	0.008	0.013**	0.007	0.003
	(2.177)	(1.597)	(1.831)	(-0.120)	(1.598)	(2.219)	(1.559)	(1.149)
Constant	-0.009***	-0.002	-0.005	0.004	-0.007*	-0.004	-0.008**	-0.015***
	(-2.938)	(-0.601)	(-1.641)	(0.780)	(-1.841)	(-1.240)	(-2.235)	(-2.662)
N	234	232	234	234	232	234	234	234

t statistics in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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Table A7: Exchange Rates and Alternative Measure of Liquidity Ratio (M2-Currency)

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat3}_t)$	0.084	0.114	0.099	-0.243***	0.214**	0.086	0.074	0.016	0.134**
	(1.285)	(1.318)	(1.574)	(-3.899)	(2.333)	(1.061)	(0.949)	(0.232)	(2.116)
$\pi_t - \pi_t^*$	-0.607***	-0.520**	-0.363*	-0.023	-0.699***	-0.067	-0.360*	-0.417*	-0.217
	(-2.901)	(-2.315)	(-1.792)	(-0.180)	(-3.007)	(-0.467)	(-1.933)	(-1.938)	(-1.385)
LiqRat3_{t-1}	0.006	0.005	0.008	0.006	0.003	0.010	0.006	0.004	0.005
	(1.170)	(0.789)	(1.503)	(1.131)	(0.424)	(1.565)	(1.080)	(0.803)	(0.930)
Constant	0.003	0.006	0.007	0.008	0.001	0.012	0.004	-0.005	0.005
	(0.474)	(0.777)	(1.157)	(1.285)	(0.111)	(1.482)	(0.553)	(-0.573)	(0.829)
N	246	246	246	246	246	246	246	246	246
adj. R^2	0.03	0.02	0.01	0.06	0.03	0.00	0.01	0.01	0.01

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A8: Exchange Rates and Alternative Measure of Liquidity Ratio (M2-Currency) with VIX

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat3}_t)$	0.085	0.117	0.108*	-0.247***	0.209**	0.095	0.083	0.018	0.135**
	(1.352)	(1.580)	(1.906)	(-4.018)	(2.519)	(1.262)	(1.120)	(0.251)	(2.192)
$\pi_t - \pi_t^*$	-0.473**	-0.287	-0.258	-0.037	-0.507**	-0.015	-0.320*	-0.374*	-0.172
	(-2.320)	(-1.484)	(-1.415)	(-0.299)	(-2.390)	(-0.115)	(-1.816)	(-1.744)	(-1.125)
ΔVIX_t	0.147***	0.365***	0.229***	-0.091***	0.309***	0.253***	0.208***	0.078**	0.115***
	(4.471)	(9.539)	(7.795)	(-2.863)	(7.344)	(6.511)	(5.441)	(2.177)	(3.677)
LiqRat3_{t-1}	0.007	0.008	0.009*	0.006	0.006	0.011*	0.008	0.005	0.005
	(1.501)	(1.429)	(1.884)	(1.088)	(0.890)	(1.858)	(1.402)	(0.930)	(1.020)
_cons	0.005	0.009	0.009	0.007	0.004	0.014*	0.006	-0.003	0.006
	(0.863)	(1.294)	(1.544)	(1.187)	(0.537)	(1.770)	(0.878)	(-0.380)	(0.926)
N	246	246	246	246	246	246	246	246	246
adj. R^2	0.10	0.28	0.21	0.08	0.21	0.15	0.11	0.02	0.06

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A9: Exchange Rates and Alternative Measure of Liquidity Ratio (M2-Currency) Instrumental Variable Regression: $\Delta(\text{VIX})$, $\text{StDev}(\text{Inf})$ and $\text{StDev}(\text{XRate})$ instrument for $\Delta(\text{LiqRat3})$

$\Delta(\text{LiqRat3}_t)$	0.753***	1.010***	0.670***	-0.408**	1.028***	0.750**	0.674**	0.014	1.089***
	(2.824)	(2.789)	(2.833)	(-1.998)	(2.682)	(2.390)	(2.333)	(0.059)	(3.118)
$\pi_t - \pi_t^*$	-0.937***	-0.939***	-0.558**	0.019	-1.263***	-0.247	-0.549**	-0.416	-0.825***
	(-3.347)	(-2.984)	(-2.261)	(0.137)	(-3.415)	(-1.361)	(-2.435)	(-1.617)	(-2.694)
LiqRat3_{t-1}	0.008	0.008	0.011*	0.005	0.005	0.016**	0.009	0.004	0.015*
	(1.252)	(1.024)	(1.851)	(0.796)	(0.597)	(2.003)	(1.318)	(0.797)	(1.902)
Constant	0.001	0.008	0.009	0.007	0.000	0.016*	0.004	-0.005	0.014
	(0.169)	(0.840)	(1.246)	(1.176)	(0.040)	(1.722)	(0.423)	(-0.544)	(1.497)
N	246	246	246	246	246	246	246	246	246

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A10: Relationship of Exchange Rates and Liquidity Ratio Feb. 2001 – April 2012

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz
$\Delta(\text{LiqRat}_t)$	0.240***	0.310***	0.143**	-0.144**	0.338***	0.203***	0.217***	0.198***
	(3.781)	(3.816)	(2.380)	(-2.371)	(4.106)	(2.664)	(2.807)	(2.771)
$\pi_t - \pi_t^*$	-1.095***	-0.725**	-0.601**	-0.261	-0.615**	-0.199	-0.522**	-0.713**
	(-3.565)	(-2.540)	(-2.372)	(-1.133)	(-2.255)	(-1.093)	(-2.125)	(-2.454)
LiqRat_{t-1}	0.008	-0.009	-0.001	-0.002	-0.003	0.001	-0.002	-0.003
	(1.181)	(-1.054)	(-0.077)	(-0.300)	(-0.309)	(0.102)	(-0.282)	(-0.381)
Constant	-0.011***	-0.001	-0.006	-0.008	-0.005	-0.006	-0.008	-0.017***
	(-2.811)	(-0.109)	(-1.633)	(-1.007)	(-1.009)	(-1.399)	(-1.565)	(-2.636)
N	135	135	135	135	135	135	135	135
adj. R^2	0.13	0.11	0.05	0.04	0.12	0.03	0.05	0.06

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A11: Exchange Rates and Liquidity Ratio with VIX Feb. 2001 – April 2012

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat}_t)$	0.182***	0.176**	0.061	-0.114*	0.248***	0.134*	0.136*	0.169**	0.137**
	(2.856)	(2.467)	(1.102)	(-1.831)	(3.127)	(1.767)	(1.827)	(2.286)	(2.250)
$\pi_t - \pi_t^*$	-0.846***	-0.391	-0.362	-0.342	-0.443*	-0.109	-0.423*	-0.632**	-0.193
	(-2.765)	(-1.586)	(-1.563)	(-1.464)	(-1.724)	(-0.614)	(-1.831)	(-2.146)	(-0.879)
ΔVIX_t	0.175***	0.430***	0.266***	-0.089*	0.301***	0.212***	0.267***	0.087	0.044
	(3.284)	(7.211)	(5.700)	(-1.730)	(4.551)	(3.493)	(4.409)	(1.453)	(0.896)
LiqRat_{t-1}	0.009	-0.004	0.001	-0.003	-0.000	0.003	0.001	-0.002	0.003
	(1.422)	(-0.541)	(0.243)	(-0.406)	(-0.047)	(0.415)	(0.149)	(-0.216)	(0.348)
Constant	-0.010***	-0.003	-0.005	-0.010	-0.005	-0.006	-0.008	-0.016**	-0.003
	(-2.694)	(-0.679)	(-1.554)	(-1.283)	(-1.191)	(-1.395)	(-1.608)	(-2.444)	(-0.827)
N	135	135	135	135	135	135	135	135	135
adj. R^2	0.19	0.36	0.24	0.06	0.23	0.11	0.17	0.06	0.03

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A12: Exchange Rates and Liquidity Ratio Instrumental Variable Regression:
StDev(Inf), StDev(XRate), and Δ(USIndProd) instrument for Δ(LiqRat) Feb. 2001 – April 2012

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat}_t)$	0.382**	0.625***	0.386***	-0.115	0.581***	0.612***	0.526**	0.199	0.636***
	(2.403)	(3.246)	(2.699)	(-0.724)	(2.983)	(2.695)	(2.579)	(1.067)	(3.095)
$\pi_t - \pi_t^*$	-1.091***	-0.734**	-0.631**	-0.341	-0.653**	-0.476*	-0.751**	-0.669*	-0.828**
	(-3.002)	(-2.358)	(-2.246)	(-1.216)	(-2.210)	(-1.839)	(-2.513)	(-1.859)	(-2.275)
LiqRat_{t-1}	0.011	-0.003	0.004	-0.003	0.002	0.006	0.002	-0.002	0.017
	(1.525)	(-0.347)	(0.526)	(-0.401)	(0.208)	(0.659)	(0.295)	(-0.215)	(1.531)
ΔVIX_t	0.129**	0.333***	0.196***	-0.089	0.231***	0.112	0.190**	0.081	-0.063
	(1.989)	(4.271)	(3.313)	(-1.457)	(2.914)	(1.359)	(2.482)	(1.134)	(-0.873)
Constant	-0.013***	-0.005	-0.010**	-0.010	-0.009*	-0.013**	-0.014**	-0.017**	-0.014**
	(-2.943)	(-1.154)	(-2.326)	(-1.021)	(-1.700)	(-2.251)	(-2.337)	(-2.045)	(-2.194)
N	135	135	135	135	135	135	135	135	135

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A13: Exchange Rates and Liquidity Ratio Instrumental Variable Regression:
Δ(VIX), StDev(Inf), StDev(XRate), and Δ(USIndProd) instrument for Δ(LiqRat) Feb. 2001 – April 2012

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
Δ(LiqRat$_t$)	0.562***	1.066***	0.631***	-0.251*	0.871***	0.791***	0.796***	0.322**	0.527***
	(3.937)	(4.934)	(4.241)	(-1.899)	(4.501)	(3.885)	(3.968)	(2.084)	(3.471)
$\pi_t - \pi_t^*$	-1.408***	-1.209***	-0.935***	-0.162	-0.905***	-0.627**	-0.995***	-0.847**	-0.676**
	(-3.941)	(-3.123)	(-2.889)	(-0.631)	(-2.770)	(-2.442)	(-3.035)	(-2.577)	(-2.275)
LiqRat$_{t-1}$	0.011	-0.005	0.004	-0.003	0.002	0.006	0.001	-0.002	0.014
	(1.412)	(-0.455)	(0.451)	(-0.452)	(0.196)	(0.594)	(0.146)	(-0.318)	(1.436)
Constant	-0.016***	-0.006	-0.013***	-0.004	-0.011*	-0.016**	-0.018***	-0.021***	-0.012**
	(-3.373)	(-1.008)	(-2.624)	(-0.425)	(-1.834)	(-2.533)	(-2.676)	(-2.708)	(-2.165)
N	135	135	135	135	135	135	135	135	135

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A14: Relationship of Exchange Rates and Liquidity Ratio May 2012 – July 2021

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat}_t)$	0.208***	0.172*	0.126	-0.051	0.181*	0.218**	0.252***	0.043	0.184**
	(2.927)	(1.735)	(1.657)	(-0.624)	(1.663)	(2.077)	(2.894)	(0.583)	(2.290)
$\pi_t - \pi_t^*$	-0.451	-0.399	0.181	0.074	-0.798	-0.169	-0.273	-0.408	-0.660*
	(-1.551)	(-0.847)	(0.445)	(0.320)	(-1.365)	(-0.623)	(-0.940)	(-1.132)	(-1.802)
LiqRat_{t-1}	0.017	0.019	0.012	0.002	0.004	0.015	0.006	0.019	0.033
	(0.976)	(0.670)	(0.614)	(0.061)	(0.187)	(0.607)	(0.328)	(1.031)	(1.507)
Constant	-0.016	-0.013	-0.008	0.002	-0.004	-0.008	-0.004	-0.024	-0.027
	(-0.973)	(-0.498)	(-0.439)	(0.079)	(-0.190)	(-0.357)	(-0.248)	(-1.165)	(-1.386)
N	111	111	111	111	111	111	111	111	111
adj. R^2	0.06	0.00	0.01	-0.02	0.01	0.02	0.06	-0.01	0.04

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A15: Exchange Rates and Liquidity Ratio with VIX May 2012 – July 2021

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat}_t)$	0.206***	0.159*	0.125*	-0.050	0.174*	0.212**	0.251***	0.043	0.181**
	(2.940)	(1.807)	(1.790)	(-0.621)	(1.770)	(2.247)	(2.958)	(0.572)	(2.389)
$\pi_t - \pi_t^*$	-0.408	-0.090	0.103	0.072	-0.402	-0.057	-0.235	-0.393	-0.607*
	(-1.419)	(-0.214)	(0.274)	(0.314)	(-0.752)	(-0.233)	(-0.829)	(-1.086)	(-1.755)
ΔVIX_t	0.074**	0.255***	0.170***	-0.082*	0.265***	0.257***	0.116**	0.026	0.152***
	(1.992)	(5.472)	(4.565)	(-1.946)	(4.996)	(5.100)	(2.557)	(0.653)	(3.794)
LiqRat_{t-1}	0.016	0.008	0.015	0.001	0.006	0.012	0.007	0.019	0.032
	(0.950)	(0.321)	(0.836)	(0.051)	(0.289)	(0.541)	(0.358)	(1.015)	(1.548)
Constant	-0.015	-0.003	-0.011	0.002	-0.005	-0.006	-0.004	-0.024	-0.026
	(-0.933)	(-0.148)	(-0.649)	(0.090)	(-0.233)	(-0.293)	(-0.259)	(-1.138)	(-1.422)
N	111	111	111	111	111	111	111	111	111
adj. R^2	0.09	0.22	0.17	0.00	0.19	0.20	0.10	-0.02	0.15

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A16: Exchange Rates and Liquidity Ratio Instrumental Variable Regression: StDev(Inf), StDev(XRate), and Δ(USIndProd) instrument for Δ(LiqRat) May 2012 – July 2021

	Euro	Australia	Canada	Japan	New Zealand	Norway	Sweden	Switz	U.K.
$\Delta(\text{LiqRat}_t)$	0.473*	0.154	0.419*	-0.313	0.395	0.808**	0.331	0.083	0.442*
	(1.973)	(0.577)	(1.768)	(-1.144)	(1.238)	(2.310)	(1.258)	(0.360)	(1.750)
$\pi_t - \pi_t^*$	-0.532	-0.087	0.032	0.178	-0.474	-0.167	-0.227	-0.419	-0.762*
	(-1.640)	(-0.186)	(0.077)	(0.679)	(-0.852)	(-0.568)	(-0.797)	(-1.077)	(-1.946)
LiqRat_{t-1}	0.015	0.008	0.013	-0.004	0.003	0.008	0.005	0.019	0.034
	(0.846)	(0.314)	(0.640)	(-0.132)	(0.126)	(0.290)	(0.284)	(1.019)	(1.540)
ΔVIX_t	0.072*	0.255***	0.169***	-0.081*	0.263***	0.253***	0.116**	0.025	0.151***
	(1.818)	(5.457)	(4.214)	(-1.835)	(4.847)	(4.282)	(2.543)	(0.645)	(3.563)
Constant	-0.014	-0.003	-0.007	0.007	-0.001	0.002	-0.003	-0.024	-0.027
	(-0.806)	(-0.145)	(-0.397)	(0.248)	(-0.034)	(0.064)	(-0.163)	(-1.149)	(-1.362)
N	111	111	111	111	111	111	111	111	111

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01

Table A17: Exchange Rates and Liquidity Ratio Instrumental Variable Regression:
Δ(VIX), StDev(Inf), StDev(XRate), and Δ(USIndProd) instrument for Δ(LiqRat) May 2012 – July 2021

Δ(LiqRat$_t$)	0.492**	0.273	0.429*	-0.323	0.463	0.863**	0.338	0.089	0.472*
	(2.015)	(0.906)	(1.676)	(-1.163)	(1.305)	(2.240)	(1.255)	(0.388)	(1.756)
$\pi_t - \pi_t^*$	-0.582*	-0.477	0.108	0.183	-0.887	-0.287	-0.264	-0.437	-0.831**
	(-1.765)	(-0.915)	(0.245)	(0.691)	(-1.449)	(-0.888)	(-0.904)	(-1.129)	(-1.997)
LiqRat$_{t-1}$	0.016	0.021	0.010	-0.004	0.000	0.010	0.005	0.020	0.035
	(0.863)	(0.714)	(0.446)	(-0.126)	(0.006)	(0.351)	(0.251)	(1.036)	(1.498)
Constant	-0.015	-0.013	-0.004	0.007	0.001	0.000	-0.003	-0.025	-0.028
	(-0.834)	(-0.527)	(-0.217)	(0.241)	(0.035)	(0.004)	(-0.147)	(-1.178)	(-1.324)
N	111	111	111	111	111	111	111	111	111

t statistics in parentheses

* p<0.1, ** p<0.05, *** p<0.01
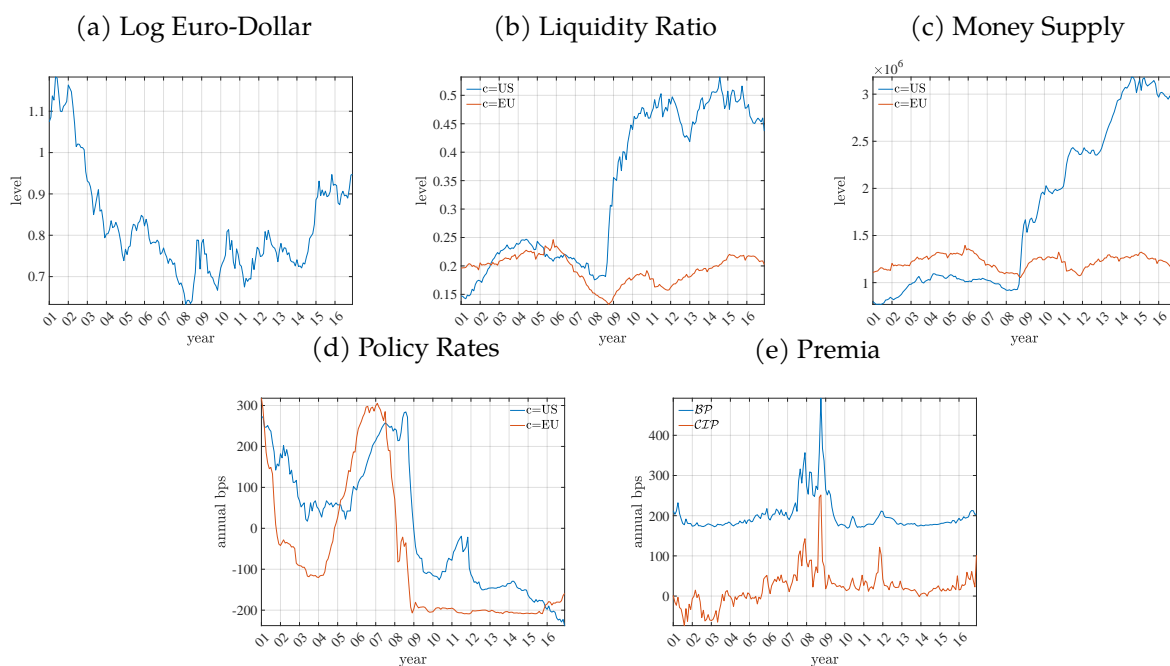
B Additional Tables Quantitative Analysis

(a) Log Euro-Dollar

(b) Liquidity Ratio

(c) Money Supply

(d) Policy Rates

(e) Premia

Figure 8: Data series

Table B1: CALIBRATED PARAMETERS

Parameter	Value	Description	Target
External Calibration			
M_{ss}^{us}/M_{ss}^{eu}	0.6841	relative money supply	normalized to exchange rate levels
Θ^b	1	global loan demand scale	normalization
ϵ	-35	loan demand elasticity	Bianchi and Bigio (2021)/symmetry
$\varsigma^{us} = \varsigma^{eu}$	35	US/EU deposit demand elasticity	Bianchi and Bigio (2021)/symmetry
$\lambda^{us} = \lambda^{eu}$	7.9	US/EU interbank market matching efficiency	Bianchi and Bigio (2021)
$\iota^{us} = \iota^{eu}$	10	US policy corridor spread	Bianchi and Bigio (2021)
$\eta^{us} = \eta^{eu}$	1/2	benchmark/symmetry	
Steady-State Estimation of Financial Variables			
$\Theta_{ss}^{d,*}$	1.0026	US deposit demand scale	To match steady-state moments
Θ_{ss}^{d}	1.0026	EU deposit demand scale	symmetry
σ_{ss}^{us}	76.8541	average US payment shock	steady-state moment targets
σ_{ss}^{eu}	21.9133	average US payment shock	steady-state moments targets
ξ_{ss}	-62.5845	average $\mathcal{CIP}$ and $\mathcal{UIP}$ wedge	steady-state moments targets
Estimates of US and EU policy variables			
$\mathbb{E}\left(i_t^{m,us}\right)$	0.9957	annualized US interest on reserves	data
$\Sigma\left(i_t^{m,us}\right)$	0.0026	std annual US policy rate	data
$\rho\left(i_t^{m,us}\right)$	0.9777	autocorrelation annual US policy rate	data
$\mathbb{E}\left(i_t^{m,eu}\right)$	1.0027	average annual Euro policy rate	data
$\Sigma\left(i_t^{m,eu}\right)$	0.0017	std annual Euro policy rate	data
$\rho\left(i_t^{m,eu}\right)$	0.9894	autocorrelation annual Euro policy rate	data
$\mathbb{E}\left(\ln M_t^{us}\right)$	6.7255	average monthly US liquid assets stock ($ Billion)	data
$\Sigma\left(\ln M_t^{us}\right)$	0.0281	std monthly US liquid assets stock	data
$\rho\left(\ln M_t^{us}\right)$	0.9894	autocorrelation monthly US liquid assets stock	data
$\mathbb{E}\left(\ln M_t^{us}\right)$	6.7255	average monthly US liquid assets stock ($ Billion)	data
$\Sigma\left(\ln M_t^{us}\right)$	0.0281	std monthly US liquid assets stock	data
$\rho\left(\ln M_t^{us}\right)$	0.9894	autocorrelation monthly US liquid assets stock	data

Table B2: ᴇꜱᴛɪᴍᴀᴛᴇᴅ Pʀᴏᴄᴇꜱꜱ

Parameter	Prior Fam	Prior Mean	Post. Mean	Post. Interval
$\Sigma^{\sigma^{us}}$	Inv. Gamma	0.150	0.100	0.091-0.108
$\Sigma^{\sigma^{eu}}$	Inv. Gamma	0.150	0.124	0.115-0.134
$\Sigma^{\Theta^{us}}$	Inv. Gamma	0.030	0.017	0.015-0.018
$\Sigma^{\Theta^{eu}}$	Inv. Gamma	0.020	0.015	0.014-0.017
Σ^{ξ}	Inv. Gamma	0.000	0.001	0.000-0.001
$\rho^{\sigma^{us}}$	Beta	0.930	0.989	0.986-0.991
$\rho^{\sigma^{eu}}$	Beta	0.930	0.954	0.931-0.973
$\rho^{\Theta^{us}}$	Beta	0.985	0.991	0.989-0.992
$\rho^{\Theta^{eu}}$	Beta	0.980	0.989	0.988-0.991
ρ^{ξ}	Beta	0.980	0.980	0.979-0.982

Table B3: Mᴏᴅᴇʟ ᴀɴᴅ Dᴀᴛᴀ Mᴏᴍᴇɴᴛꜱ

Moment	Data	Simulated Moment
Steady-State Targets		
Mean of $\mathcal{CIP}$	13.407	16.030
Mean of $\mathcal{BP}$	194.605	196.044
Mean of μ^{us}	0.226	0.233
Mean of μ^{eu}	0.222	0.232
Mean of e	1.251	1.281
Untargetted Moments		
Std. of $\mathcal{CIP}$	42.672	121.597
Std. of $\mathcal{BP}$	42.271	103.433
Std. of μ^{us}	0.133	0.036
Std. of μ^{eu}	0.025	0.041
Std. of e	0.167	0.183
AR(1) Coef. of $\mathcal{CIP}$	0.801	0.947
AR(1) Coef. of $\mathcal{BP}$	0.879	0.955
AR(1) Coef. of μ^{us}	0.989	0.957
AR(1) Coef. of μ^{eu}	0.986	0.955
AR(1) Coef. of e	0.963	0.953

Figure 9: Euro per Dollar Exchange Rate, March 2020

Table B4: U.S. Treasury Yields, March 2020

Date	1 Mo	2 Mo	3 Mo	6 Mo	1 Yr	2 Yr	3 Yr	5 Yr	7 Yr	10 Yr	20 Yr	30 Yr
3/2/2020	1.41	1.27	1.13	0.95	0.89	0.84	0.85	0.88	1.01	1.1	1.46	1.66
3/3/2020	1.11	1.05	0.95	0.83	0.73	0.71	0.72	0.77	0.91	1.02	1.44	1.64
3/4/2020	1	0.87	0.72	0.68	0.59	0.67	0.68	0.75	0.9	1.02	1.45	1.67
3/5/2020	0.92	0.83	0.62	0.53	0.48	0.59	0.61	0.67	0.81	0.92	1.34	1.56
3/6/2020	0.79	0.64	0.45	0.41	0.39	0.49	0.53	0.58	0.69	0.74	1.09	1.25
3/9/2020	0.57	0.52	0.33	0.27	0.31	0.38	0.4	0.46	0.56	0.54	0.87	0.99
3/10/2020	0.57	0.55	0.44	0.43	0.43	0.5	0.58	0.63	0.73	0.76	1.16	1.28
3/11/2020	0.42	0.42	0.42	0.4	0.4	0.5	0.58	0.66	0.78	0.82	1.13	1.3
3/12/2020	0.41	0.33	0.33	0.37	0.39	0.5	0.58	0.66	0.82	0.88	1.27	1.49
3/13/2020	0.33	0.3	0.28	0.38	0.38	0.49	0.58	0.7	0.89	0.94	1.31	1.56
3/16/2020	0.25	0.25	0.24	0.29	0.29	0.36	0.43	0.49	0.67	0.73	1.1	1.34
3/17/2020	0.12	0.18	0.19	0.24	0.3	0.47	0.54	0.66	0.91	1.02	1.45	1.63
3/18/2020	0.04	0.03	0.02	0.08	0.21	0.54	0.66	0.79	1.08	1.18	1.6	1.77
3/19/2020	0.04	0.04	0.04	0.06	0.2	0.44	0.53	0.66	1	1.12	1.56	1.78
3/20/2020	0.04	0.05	0.05	0.05	0.15	0.37	0.41	0.52	0.82	0.92	1.35	1.55
3/23/2020	0.01	0.04	0.02	0.08	0.17	0.28	0.31	0.38	0.63	0.76	1.12	1.33
3/24/2020	0.01	0.01	0.01	0.09	0.25	0.38	0.44	0.52	0.75	0.84	1.19	1.39
3/25/2020	0	0	0	0.07	0.19	0.34	0.41	0.56	0.77	0.88	1.23	1.45
3/26/2020	0.01	0.01	0	0.04	0.13	0.3	0.36	0.51	0.72	0.83	1.2	1.42
3/27/2020	0.01	0.03	0.03	0.02	0.11	0.25	0.3	0.41	0.6	0.72	1.09	1.29
3/30/2020	0.04	0.07	0.12	0.12	0.14	0.23	0.29	0.39	0.57	0.7	1.1	1.31
3/31/2020	0.05	0.12	0.11	0.15	0.17	0.23	0.29	0.37	0.55	0.7	1.15	1.35

Source: U.S. Department of Treasury

Appendix not for Publication

C Expressions for $\{\Psi^+, \Psi^-, \chi^+, \chi^-\}$

Here we reproduce formulas derived from Proposition 1 in Bianchi and Bigio (2017). That proposition gives us the formulas for the liquidity yield function and the matching probabilities as functions of the tightness of the interbank market.

The average interbank rate is:

$$R^f = (1 - \bar{\eta}(\theta))R^w + \bar{\eta}(\theta) R^m$$

where $\bar{\eta}(\theta)$ is an endogenous bargaining power given by

$$\bar{\eta}(\theta) \equiv \begin{cases} \frac{\theta}{\theta-1}\left(\left(\frac{\bar{\theta}}{\theta}\right)^\eta - 1\right)(\exp(\lambda) - 1)^{-1} & \text{if } \theta > 1 \\ \eta & \text{if } \theta = 1 \\ \frac{\theta(1-\bar{\theta})-\bar{\theta}}{\theta(1-\theta)}\left(\left(\frac{\bar{\theta}}{\theta}\right)^\eta - 1\right)(\exp(\lambda) - 1)^{-1} & \text{if } \theta < 1 \end{cases} .$$

and η is a parameter associated with the bargaining power of banks with reserve deficits in each trade—a Nash bargaining coefficient. In addition, $\bar{\theta}$ represents the market tightness after the interbank-market trading session is over:

$$\bar{\theta} = \begin{cases} 1 + (\theta - 1)\exp(\lambda) & \text{if } \theta > 1 \\ 1 & \text{if } \theta = 1 \\ (1 + (\theta^{-1} - 1)\exp(\lambda))^{-1} & \text{if } \theta < 1 \end{cases} .$$

The parameter λ captures the matching efficiency of the interbank market. Trading probabilities are given by

$$\Psi^+ = \begin{cases} 1 - e^{-\lambda} & \text{if } \theta \geq 1 \\ \theta(1 - e^{-\lambda}) & \text{if } \theta < 1 \end{cases}, \qquad \Psi^- = \begin{cases} (1 - e^{-\lambda})\theta^{-1} & \text{if } \theta > 1 \\ 1 - e^{-\lambda} & \text{if } \theta \leq 1 \end{cases} . \tag{27}$$

Finally, using 7 and 6, we arrive at the parameters of the liquidity yield function χ:

$$\bar{\chi}^+ = (R^w - R^m)\left(\frac{\bar{\theta}}{\theta}\right)^\eta \left(\frac{\theta^\eta\bar{\theta}^{1-\eta} - \theta}{\bar{\theta} - 1}\right) \text{ and } \bar{\chi}^- = (R^w - R^m)\left(\frac{\bar{\theta}}{\theta}\right)^\eta \left(\frac{\theta^\eta\bar{\theta}^{1-\eta} - 1}{\bar{\theta} - 1}\right). \tag{28}$$

D Proofs

D.1 Preliminaries

Here we provide some intermediate results that we use to prove the propositions.

Recall that the liquidity ratio is denoted by $\mu \equiv m/d$ and $\theta = S^-/S^+$ where $S^- = -\int \min\{s, 0\} \, d\Phi(\omega)$, $S^+ = \int \max\{s, 0\} \, d\Phi(\omega)$ and $s = m + \omega d$. Then,

$$
\begin{aligned}
\theta &= -\frac{\int_{\{s<0\}} s \cdot d\Phi(\omega; \sigma)}{\int_{\{s>0\}} s \cdot d\Phi(\omega; \sigma)}, \\
&= -\frac{m\Phi(\{s < 0\}; \sigma) + d\int_{\{s<0\}} \omega \cdot d\Phi(\omega; \sigma)}{m(1 - \Phi(\{s > 0\}; \sigma)) + d\int_{\{s \geq 0\}} \omega \cdot d\Phi(\omega; \sigma)}.
\end{aligned}
$$

Note that $s < 0$ occurs when $\omega < -\mu$. Therefore, we express the interbank market tightness as:

$$
\theta = -\frac{\int_{-\infty}^{-\mu} (\mu + \omega) \cdot d\Phi(\omega; \sigma)}{\int_{-\mu}^{\infty} (\mu + \omega) \cdot d\Phi(\omega; \sigma)}. \tag{29}
$$

With abuse of notation, define $\theta(\mu, \sigma)$ as the function that maps μ and σ into a value of θ (thus, in equilibrium, $\theta = \theta(\mu, \sigma)$). We have the following Lemma:

Lemma 3. *Interbank market tightness is decreasing in the liquidity ratio. That is, $\frac{d\theta}{d\mu} < 0$. Moreover, $\theta \in [0, 1]$.*

Proof. From (29), using Leibniz rule, we obtain

$$
\frac{d\theta}{d\mu} = \theta\left(\frac{\Phi(-\mu; \sigma)}{\int_{-\infty}^{-\mu} (\mu + \omega) \cdot d\Phi(\omega; \sigma)} - \frac{1 - \Phi(-\mu; \sigma)}{\int_{-\mu}^{\infty} (\mu + \omega) \cdot d\Phi(\omega; \sigma)}\right). \tag{30}
$$

By definition of conditional expectation:

$$
\mathbb{E}[\mu + \omega | \omega < -\mu] = \int_{-\infty}^{-\mu} (\mu + \omega) \cdot d\Phi(\omega; \sigma) / \Phi(-\mu; \sigma),
$$

and

$$
\mathbb{E}[\mu + \omega | \omega > -\mu] = \int_{-\mu}^{\infty} (\mu + \omega) \cdot d\Phi(\omega; \sigma) / (1 - \Phi(-\mu; \sigma)).
$$

Replacing these definitions into (30), we obtain:

$$\frac{d\theta}{d\mu} = \theta \cdot \left(\frac{1}{\mathbb{E}\left[\mu + \omega | \omega < -\mu\right]} - \frac{1}{\mathbb{E}\left[\mu + \omega | \omega > -\mu\right]} \right) < 0,$$

where the inequality follows because $\mathbb{E}\left[\mu + \omega | \omega < -\mu\right] < 0$ and $\mathbb{E}\left[\mu + \omega | \omega > -\mu\right] > 0$.

Finally, the bounds on θ follow because $\lim_{\mu \to \infty} \theta = 0$ and $\theta = 1$ if $\mu = 0$. $\qquad \square$

Next, we obtain the derivative of interbank market tightness with respect to σ.

Lemma 4. *Under Assumption 1, we have that $\frac{\partial \theta}{\partial \sigma} > 0$.*

Proof. Passing the differential operator inside the integrals in the numerators, we have that:

$$\begin{aligned}
\frac{\partial \theta}{\partial \sigma} &= \theta \cdot \left(\frac{\int_{-\infty}^{-\mu} (\mu + \omega)\, \phi_\sigma d\omega}{\int_{-\infty}^{-\mu} (\mu + \omega) \cdot d\Phi(\omega; \sigma)} - \frac{\int_{-\mu}^{\infty} (\mu + \omega)\, \phi_\sigma d\omega}{\int_{-\mu}^{\infty} (\mu + \omega) \cdot d\Phi(\omega; \sigma)} \right) \\
&= \theta \cdot \left(\frac{\partial}{\partial \sigma} \left[\log \left(\frac{\int_{-\infty}^{-\mu} (\mu + \omega) \cdot d\Phi(\omega; \sigma)}{\int_{-\mu}^{\infty} (\mu + \omega) \cdot d\Phi(\omega; \sigma)} \right) \right] \right).
\end{aligned}$$

Since the withdrawal shock is zero mean,

$$\int_{-\infty}^{-\mu} (\mu + \omega) \cdot d\Phi(\omega; \sigma) + \int_{-\mu}^{\infty} (\mu + \omega) \cdot d\Phi(\omega; \sigma) = \mu.$$

Therefore, identity this condition into the derivative just above we obtain:

$$\frac{\partial \theta}{\partial \sigma} = \log \left(\frac{\mu - \int_{-\mu}^{\infty} (\mu + \omega) \cdot d\Phi(\omega; \sigma)}{\int_{-\mu}^{\infty} (\mu + \omega) \cdot d\Phi(\omega; \sigma)} \right).$$

Therefore, $\frac{\partial \theta}{\partial \sigma} > 0$ holds if and only if:

$$\frac{\partial}{\partial \sigma} \left[\int_{-\infty}^{-\mu} (\mu + \omega) \cdot d\Phi(\omega; \sigma) \right] < 0.$$

Using the integration by parts formula:

$$\begin{aligned}
\int_{-\infty}^{-\mu} (\mu + \omega)\, \phi_\sigma(\omega; \sigma)\, d\omega &= (\mu + \omega)\, \Phi_\sigma(\omega; \sigma) \big|_{-\infty}^{-\mu} - \int_{-\infty}^{-\mu} \Phi_\sigma(\omega; \sigma)\, d\omega \\
&= - \int_{-\infty}^{-\mu} \Phi_\sigma(\omega; \sigma)\, d\omega < 0
\end{aligned}$$

where the last equality follows from $\lim_{\omega \to -\infty} ((\mu + \omega))\, \Phi_\sigma(\omega; \sigma) = \frac{\partial}{\partial \sigma} \left[\lim_{\omega \to -\infty} ((\mu + \omega))\, \Phi(\omega; \sigma) \right] =$

0 and the strict inequality follows from Assumption 1. We conclude that, $\frac{\partial \theta}{\partial \sigma} > 0$. □

We will also use the results from the following Lemma.

Lemma 5. *The liquidity coefficients have the following derivatives:*

$$\frac{\partial \chi^+}{\partial \mu} = \frac{\partial \chi^+}{\partial \theta} \frac{\partial \theta}{\partial \mu} < 0 \quad and \quad \frac{\partial \chi^-}{\partial \mu} = \frac{\partial \chi^-}{\partial \theta} \frac{\partial \theta}{\partial \mu} < 0, \tag{31}$$

$$\frac{\partial \chi^+}{\partial \sigma} = \frac{\partial \chi^+}{\partial \theta} \frac{\partial \theta}{\partial \sigma} > 0 \quad and \quad \frac{\partial \chi^-}{\partial \mu} = \frac{\partial \chi^-}{\partial \theta} \frac{\partial \theta}{\partial \sigma} > 0, \tag{32}$$

$$\frac{\partial \bar{\chi}^+}{\partial P_t} = \frac{\bar{\chi}^+}{P_t} \quad and \quad \frac{\partial \bar{\chi}^-(\theta)}{\partial P_t} = \frac{\bar{\chi}^-}{P_t}. \tag{33}$$

Proof. Notice first that $\frac{\partial \chi^+}{\partial \theta} > 0$ and $\frac{\partial \chi^-}{\partial \theta} > 0$ is an immediate result from their definitions in equations (28). Applying Lemmas 3 and 4, we obtain respectively (31) and (32).

In addition, we can express (28) as

$$\bar{\chi}^+ = \frac{P_t}{P_{t+1}} \left(i^w - i^m \right) \left(\frac{\bar{\theta}}{\theta} \right)^\eta \left(\frac{\theta^\eta \bar{\theta}^{1-\eta} - \theta}{\bar{\theta} - 1} \right), \ \bar{\chi}^- = \frac{P_t}{P_{t+1}} \left(i^w - i^m \right) \left(\frac{\bar{\theta}}{\theta} \right)^\eta \left(\frac{\theta^\eta \bar{\theta}^{1-\eta} - 1}{\bar{\theta} - 1} \right) \tag{34}$$

Equation (33) follows immediately. □

It is useful to define $\mathcal{L}(\mu, \sigma, P)$ to be the bond liquidity premium as a function of the liquidity ratio, the index σ and the current price level. That is,

$$\mathcal{L}(\mu, \sigma, P) = (1 - \Phi(-\mu, \sigma)) \cdot \bar{\chi}^+ (\theta(\mu, \sigma), P) + \Phi(-\mu, \sigma) \cdot \bar{\chi}^- (\theta(\mu, \sigma), P) \tag{35}$$

In equilibrium $\mathcal{L}(\mu, \sigma, P) = R^b - R^m$. We have the following result.

Lemma 6. *The liquidity bond premium is decreasing in the liquidity ratio and increasing in volatility. That is, $\mathcal{L}_\mu < 0$ and $\mathcal{L}_\sigma > 0$. In addition, $\mathcal{L}_P = -\mathcal{L}/P$.*

Proof. From (35), differentiating $\mathcal{L}$ with respect to μ:

$$\mathcal{L}_\mu = \left[(1 - \Phi(-\mu, \sigma)) \cdot \chi_\theta^+ + \Phi(-\mu, \sigma) \cdot \chi_\theta^- \right] - \left(\bar{\chi}^- - \bar{\chi}^+ \right) \phi (-\mu, \sigma). \tag{36}$$

Using that $\frac{\partial \theta}{\partial \mu} < 0$ from Lemma 3 and that $\bar{\chi}^- > \bar{\chi}^+$, we arrive at $\mathcal{L}_\mu < 0$.

From (35), differentiating $\mathcal{L}$ with respect to σ yields:

$$\mathcal{L}P_\sigma = \frac{\partial \theta}{\partial \sigma} \left[(1 - \Phi(-\mu, \sigma)) \cdot \chi_\theta^+ + \Phi(-\mu, \sigma) \cdot \chi_\theta^- \right] + \left(\bar{\chi}^- - \bar{\chi}^+ \right) \Phi_\sigma (-\mu, \sigma). \tag{37}$$

Using that $\frac{\partial\theta}{\partial\sigma} > 0$ from Lemma 4 and that $\bar{\chi}^- > \bar{\chi}^+$, we conclude that $\mathcal{L}_\sigma > 0$. Finally, the expression for $\mathcal{L}_P$ follows directly from differentiating $\mathcal{L}$ with respect to P in (33). $\qquad\square$

We now proceed with the proofs and use that these properties apply for both euros and dollars.

D.2 Proof of Proposition 1

Proof. **Part i).** By definition, the liquidity ratio μ^* is given by

$$\mu^*(P^*, D^*) = \frac{M^*/P^*}{D^*} \tag{38}$$

where we made explicit the dependence of μ^* on (P^*, D^*). Using that M^* is exogenously given, totally differentiating (38) yields

$$d\mu^* = -\mu^* \left(\frac{dP^*}{P^*} + \frac{dD^*}{D^*} \right). \tag{39}$$

The dollar liquidity premium is

$$R^b - (1 + i^{m,*}) \frac{P^*}{\mathbb{E}[P^*(X')]} = \mathcal{L}^*(\mu^*(P^*, D^*), P^*). \tag{40}$$

Totally differentiating (40) with respect to P^* and D^*, and using (39), we obtain:

$$- R^{m,*} \left(\frac{dP^*}{P^*} \right) = -\mathcal{L}^*_{\mu^*} \left[\mu \left(\frac{dP^*}{P^*} + \frac{dD^*}{D^*} \right) \right] + \mathcal{L}^*_P dP^* \tag{41}$$

where $\mathbb{E}[P^*(X')]$ remains constant because the shock is i.i.d. and the loan rate is constant at $R^b = 1/\beta$.

Using $\mathcal{L}^*_{P*} = \frac{\mathcal{L}^*}{P^*}$ from Lemma 6, $R^b = R^{m,*} + \mathcal{L}^*$ and replacing in (41), we arrive to

$$\frac{d\log P^*}{d\log D^*} = \frac{\mathcal{L}^*_{\mu^*}\mu^*}{R^b - \mathcal{L}^*_{\mu^*}\mu^*} \in (-1, 0). \tag{42}$$

The bounds follows immediately because $\mathcal{L}^*_\mu < 0$ as established in Lemma 6 and from $R^b > 0$.

Notice also that the euro bond premium remains constant. To see this, we can replace $\mu = (M/P)/D$ in (17) and use (29) to obtain

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$$R^b - (1 + i^m)\frac{P}{\mathbb{E}[P(X')]} = \left(1 - \Phi\left(-\frac{M/P}{D}\right)\right)\bar{\chi}^+(\theta((M/P)/D, \sigma)) +$$

$$\Phi\left(-\frac{M/P}{D}\right)\bar{\chi}^-(\theta((M/P)/D, \sigma)). \quad (43)$$

From (43), it follows that P must be constant and thus μ and $\mathcal{L}$ are also constant. As a result, $d\mathcal{L}^* = d\mathcal{DLP}$, $d\mathcal{L}_{\mu^*}^* = d\mathcal{DLP}_{\mu^*}$.

By the law of one price and using that P remains constant, we then have $\frac{d\log e}{d\log D^*} = -\frac{\mathcal{L}_\mu^* \mu^*}{R^b - \mathcal{L}_\mu^* \mu^*}$ which implies an appreciation of the dollar. Finally, we can rewrite (41) as $\bar{R}^{m,*}(d\log e) = d\mathcal{L}^* = d\mathcal{DLP}$.

Part ii). When the shock is permanent, expected inflation remains constant. Moreover, given that nominal policy rates and expected inflation are constant, we have from (18) that $\mathcal{L}^*$ is constant. Hence, $\mathcal{DLP}$ is constant. Furthermore, the fact that $\mathcal{L}^*$ is constant, implies that μ must also be constant. Thus, using that (39) and that M^* is constant, we have from the law of one price that:

$$\frac{d\log e}{d\log D^*} = -\frac{d\log P^*}{d\log D^*} = 1.$$

$\square$

D.3   Proof of Proposition 2

Proof. **Part i).** Totally differentiating (38) with respect to P^* yields

$$d\mu^* = -\mu^* \left(\frac{dP^*}{P^*}\right). \quad (44)$$

The dollar liquidity premium is

$$R^b - (1 + i^{m,*})\frac{P^*}{\mathbb{E}[P^*(X')]} = \mathcal{L}^*(\mu^*(P^*, \sigma^*), P^*). \quad (45)$$

Totally differentiating (45) with respect to P^* and σ^* and using (44) yields:

$$-R^{m,*}\left(\frac{dP^*}{P^*}\right) = -\mathcal{L}_\mu^*\left[\mu\left(\frac{dP^*}{P^*}\right)\right] + \mathcal{L}_{\sigma^*}^* d\sigma^* + \mathcal{L}_P^* dP^* \quad (46)$$

where we used that $\mathbb{E}[P^*(X')]$ is constant because the shock is i.i.d. and $R^b = 1/\beta$.

Using $\mathcal{L}_{P*}^* = \frac{\mathcal{L}^*}{P^*}$ from Lemma 6, $R^b = R^{m,*} + \mathcal{L}^*$, and replacing in (44) , we obtain

$$\frac{d\log P^*}{d\log \sigma^*} = -\frac{\mathcal{L}_{\sigma*}^* \sigma}{R^b - \mathcal{L}_{\mu}^* \mu^*} < 0 \tag{47}$$

where the sign follows from Lemma 6. Notice also that the euro bond premium remains constant, and so do P, μ and $\mathcal{L}$, as demonstrated in the proof of Proposition 1.

By the law of one price, and using that P remains constant, we then have $\frac{d\log e}{d\log D^*} = \frac{\mathcal{L}_{\sigma}^* \sigma^*}{R^b - \mathcal{L}_{\mu}^* \mu^*}$ which implies an appreciation of the dollar. Finally, we can rewrite (46) as $\bar{R}^{m,*}(d\log e) = d\mathcal{L}^* = d\mathcal{DLP}$.

Part ii). When the shock is permanent, expected inflation is constant. Given that nominal policy rates are constant, $\mathcal{L}^*$ and $\mathcal{DLP}$ are constant. Thus,

$$\mathcal{L}_{\mu*}^* d\mu^* + \mathcal{L}_{\sigma*}^* d\sigma^* = 0 \tag{48}$$

and so

$$\frac{d\log \mu^*}{d\log \sigma^*} = -\frac{\mathcal{L}_{\sigma*}^* \sigma^*}{\mathcal{L}_{\mu*}^* \mu^*} > 0 \tag{49}$$

where the sign follows from $\mathcal{L}_{\mu*}^* < 0$ and $\mathcal{L}_{\sigma*}^* > 0$ from Lemma 6. Using that $d\log \mu^* = -d\log P^*$, from the law of one price, $\frac{d\log e^*}{d\log \sigma^*} = \frac{d\log \mu^*}{d\log \sigma^*}$. □

D.4 Approximation to Mean Reverting Shocks

Proof. We now derive approximate analogues to propositions 1 and 2 for cases where shocks are mean reverting. In particular, shocks follow a log AR(1) process:

$$\log (x_t) = (1 - \rho^x) \log (x_{ss}) + \rho^x \cdot \log (x_{t-1}) + \Sigma^x \varepsilon_t^x. \tag{50}$$

We have the following result. We use x_{ss} to refer to the deterministic steady-state value of any variable x. The proof extends the results in Propositions 1 and 2. We first show this intermediate result. In the model, prices are a function of the aggregate state, X. Thus, an equilibrium will feature a function $P^*(X_t)$ such that $P_t^* = P^*(X_t)$. Then, near the steady state, using a Taylor expansion of first-order with respect to the variable x. We have that:

$$\log P_t^* \approx \log P_{ss}^* + \frac{P_x^*(x_{ss}) x_{ss}}{P_{ss}^*} \frac{x_t - x_{ss}}{x_{ss}}.$$

Thus, we have that for small deviations around the steady state:

$$d\log P_t^* \approx \frac{P_x^*(x_{ss}) x_{ss}}{P_{ss}^*} d\log x_t. \tag{51}$$

Shifting this condition forward:

$$d \log P_{t+1}^* \approx \frac{P_x^* (x_{ss}) x_{ss}}{P_{ss}^*} d \log x_{t+1}$$

Taking expectations:

$$\mathbb{E}\left[d \log P_{t+1}^*\right] \approx \frac{P_x^* (x_{ss}) x_{ss}}{P_{ss}^*} \rho^x d \log x_t. \tag{52}$$

Dividing the left-hand side of (52) by (51),

$$\frac{\mathbb{E}\left[d \log P_{t+1}^*\right]}{d \log P_t^*} = \rho^x d \log x_t. \tag{53}$$

Next, we proof the main items of the propositions. The proof uses that for either currency:

$$\frac{\partial \bar{\chi}^+}{\partial P_{t+1}} = -\frac{\bar{\chi}^+}{\mathbb{E}\left[P_{t+1}\right]}, \text{ and } \frac{\partial \bar{\chi}^-(\theta)}{\partial P_{t+1}} = -\frac{\bar{\chi}^-}{\mathbb{E}\left[P_{t+1}\right]}. \tag{54}$$

Hence:

$$\mathcal{L}_{P_{t+1}^*}^* = -\frac{\mathcal{L}^*}{P_{t+1}^*}$$

Recall that the dollar liquidity premium can be expressed as

$$R^b - (1 + i^{m,*})\frac{P_t^*}{\mathbb{E}\left[P_{t+1}^*\right]} = \mathcal{L}^*(\mu^*(P^*, D^*), P_t^*, P_{t+1}^*), \tag{55}$$

where we now make explicit that $\mathcal{L}^*$ depends on both P_t and P_{t+1}.

Part (i). We present here the proof for item (i). Totally differentiating (55) with respect to P_t, P_{t+1}, and D^* and using (39) near the steady state, we obtain

$$-R^{m,*}\left(\frac{dP_t^*}{P_t^*}\right) + R^{m,*}\frac{\mathbb{E}\left[dP_{t+1}^*\right]}{\mathbb{E}\left[P_{t+1}^*\right]} = -\mathcal{L}_{\mu^*}^* \mu^*\left(\frac{dP_t^*}{P_t^*} + \frac{dD_t^*}{D_t^*}\right) + \mathcal{L}_{P_t^*}^* dP_t^* - \mathcal{L}_{P_{t+1}^*}^* \mathbb{E}\left[dP_{t+1}^*\right]. \tag{56}$$

Then, collecting terms:

$$-\left(R^{m,*} + \mathcal{L}^*\right)\left(1 - \frac{\mathbb{E}\left[d \log P_{t+1}^*\right]}{d \log P_t^*}\right) d \log P_t^* = -\mathcal{L}_{\mu^*}^* \mu^*\left(\frac{dP_t^*}{P_t^*} + \frac{dD_t^*}{D_t^*}\right). \tag{57}$$

Substituting $R^b = R^{m,*} + \mathcal{L}^*$ and (53), we obtain:

$$R^b\left(1 - \rho^{D^*}\right) d \log P_t^* \approx \mathcal{L}_{\mu^*}^* \mu^*\left(\frac{dP_t^*}{P_t^*} + \frac{dD_t^*}{D_t^*}\right).$$

Thus, we obtain

$$\frac{d\log P^*}{d\log D^*} \approx \frac{\mathcal{L}^*_{\mu^*}\mu^*}{(1-\rho^{D^*})R^b - \mathcal{L}^*_{\mu^*}\mu^*} < 0.$$

Then, it follows from the law of one price and the differential form of μ that

$$\epsilon^e_{D^*} \equiv \frac{d\log e}{d\log D^*} \approx -\frac{\mathcal{L}^*_{\mu^*}\mu^*}{(1-\rho^{D^*})R^b - \mathcal{L}^*_{\mu^*}\mu^*} \in (0,1),$$

and

$$\epsilon^e_{\mu^*} \equiv \frac{d\log \mu}{d\log D^*} \approx -\frac{(1-\rho^{D^*})R^b}{(1-\rho^{D^*})R^b - \mathcal{L}^*_{\mu^*}\mu^*} \in (-1,0).$$

Part (ii). We present here the proof for item (ii). It follows the same steps as in Part (i): We totally differentiate (55) with respect to P_t, P_{t+1}, and σ^* and using (39) for the case where $dD^* = 0$. We obtain:

$$-R^{m,*}\left(\frac{dP_t^*}{P_t^*}\right) + R^{m,*}\frac{\mathbb{E}\left[dP_{t+1}^*\right]}{\mathbb{E}\left[P_{t+1}^*\right]} = \mathcal{L}^*_{\sigma^*}d\sigma^* - \mathcal{L}^*_{\mu^*}\mu^*\left(\frac{dP_t^*}{P_t^*}\right) + \mathcal{L}^*_{P_t^*}dP_t^* - \mathcal{L}^*_{P_{t+1}^*}\mathbb{E}\left[dP_{t+1}^*\right]. \quad (58)$$

Collecting terms and using the same identities that we use to derive 57, we arrive at:

$$\left(R^b\left(1-\rho^{\sigma^*}\right) - \mathcal{L}^*_{\mu^*}\mu^*\right)d\log P_t^* \approx -\mathcal{L}^*_{\sigma^*}d\sigma^*.$$

Therefore, we obtain:

$$\frac{d\log P^*}{d\log \sigma^*} \approx \frac{-\mathcal{L}^*_{\sigma^*}d\sigma^*}{(1-\rho^{\sigma^*})R^b - \mathcal{L}^*_{\mu^*}\mu^*} < 0.$$

Then using that $\mu^* = M^*/(P^*D^*)$ and that $e = P/P^*$ and that P, M^* and D^* are constant, we arrive at:

$$\frac{d\log \mu^*}{d\log \sigma^*} \approx \frac{d\log e}{d\log \sigma^*} = -\frac{d\log P^*}{d\log \sigma^*} = \frac{\mathcal{L}^*_{\sigma^*}d\sigma^*}{(1-\rho^{\sigma^*})R^b - \mathcal{L}^*_{\mu^*}\mu^*} > 0.$$

$\square$

D.5   Proof of Proposition 3

We again consider that any shock x follows a log AR(1) process:

$$\log(x_t) = (1-\rho^x)\log(x_{ss}) + \rho^x \cdot \log(x_{t-1}) + \Sigma^x \varepsilon_t^x.$$

We consider only shocks to dollar funding risk and the dollar funding scale and that $Var\left(\varepsilon_t^x\right) = 1$ for all shocks. Thus

$$Var\left(x_t\right) = \frac{\left(\Sigma^x\right)^2}{\left(1 - \left(\rho^x\right)^2\right)}. \tag{59}$$

Consider a univariate linear regression of $\Delta \log e^*$ against $\Delta \log \mu^*$ where $\Delta x_t = x_t - x_{t-1}$. The regression coefficient is a function of two moments:

$$\gamma_{\mu^*}^{e^*} = \frac{CoV\left(\Delta \log e^*, \Delta \log \mu^*\right)}{Var\left(\Delta \log \mu^*\right)}. \tag{60}$$

Consider an endogenous variable Y_t in the model. An equilibrium will feature a function $Y\left(X_t\right)$ such that $Y_t = Y\left(X_t\right)$, where X_t is the exogenous state. Then, using a first-order Taylor expansion:

$$\log Y_t \approx \log Y_{ss} + \sum_{x \in X} \frac{Y_x\left(x_{ss}\right) \cdot x_{ss}}{Y_{ss}} \frac{x_t - x_{ss}}{x_{ss}} \text{ for } x \in X.$$

Therefore, we have that:

$$\Delta \log Y_t \approx \sum_{x \in X} \frac{Y_x\left(x_{ss}\right) \cdot x_{ss}}{Y_{ss}} \left(\frac{x_t - x_{ss}}{x_{ss}} - \frac{x_{t-1} - x_{ss}}{x_{ss}}\right).$$

Near a steady state:

$$\frac{x_t - x_{ss}}{x_{ss}} - \frac{x_{t-1} - x_{ss}}{x_{ss}} \approx \Delta \log\left(x_t\right) = \rho^x \cdot \left(\log\left(x_{t-1}\right) - \log\left(x_{ss}\right)\right) + \Sigma^x \varepsilon_t^x.$$

Using this identity,

$$\Delta \log Y_t \approx \sum_{x \in X} \frac{Y_x\left(x_{ss}\right) \cdot x_{ss}}{Y_{ss}} \left(\rho^x \cdot \left(\log\left(x_{t-1}\right) - \log\left(x_{ss}\right)\right) + \Sigma^x \varepsilon_t^x\right).$$

Then, for small shocks the log-deviation from steady-state is approximately the elasticity near steady state.

$$\frac{Y_x\left(x\right) \cdot x}{Y_{ss}} = \epsilon_x^Y.$$

Hence, we have that $\Delta \log e_t^*$ and $\Delta \log \mu_t^*$ follow:

$$\begin{aligned}
\Delta \log e_t^* &= \epsilon_{\sigma^*}^{e^*} \left(\rho^{\sigma^*} \cdot \left(\log\left(\sigma_{t-1}^*\right) - \log\left(\sigma_{ss}^*\right)\right) + \Sigma^{\sigma^*} \varepsilon_t^{\sigma^*}\right) \dots \\
&\quad + \epsilon_{D^*}^{e^*} \left(\rho^{D^*} \cdot \left(\log\left(D_{t-1}^*\right) - \log\left(D_{ss}^*\right)\right) + \Sigma^{D^*} \varepsilon_t^{D^*}\right).
\end{aligned} \tag{61}$$

Likewise, for the dollar liquidity ratio:

$$\Delta \log \mu_t^* = \epsilon_{\sigma*}^{\mu*} \left(\rho^{\sigma*} \cdot \left(\log \left(\sigma_{t-1}^* \right) - \log \left(\sigma_{ss}^* \right) \right) + \Sigma^{\sigma*} \varepsilon_t^{\sigma*} \right) \dots$$
$$+ \epsilon_{D*}^{\mu*} \left(\rho^{D*} \cdot \left(\log \left(D_{t-1}^* \right) - \log \left(D_{ss}^* \right) \right) + \Sigma^{D*} \varepsilon_t^{D*} \right). \qquad (62)$$

From, (62) variance of the change in the liquidity ratio is:

$$Var \left(\Delta \log \mu^* \right) = \left(\epsilon_{\sigma*}^{\mu*} \right)^2 \left(\left(\rho^{\sigma*} \right)^2 Var \left(\sigma^* \right) + \left(\Sigma^{\sigma*} \right)^2 \right) + \left(\epsilon_{D*}^{\mu*} \right)^2 \left(\left(\rho^{D*} \right)^2 Var \left(D^* \right) + \left(\Sigma^{D*} \right)^2 \right).$$

Substituting (59) into the equation above:

$$Var \left(\Delta \log \mu^* \right) = \left(\epsilon_{\sigma*}^{\mu*} \right)^2 \left(\left(\rho^{\sigma*} \right)^2 \frac{\left(\Sigma^{\sigma*} \right)^2}{\left(1 - \left(\rho^{\sigma*} \right)^2 \right)} + \left(\Sigma^{\sigma*} \right)^2 \right) + \left(\epsilon_{D*}^{\mu*} \right)^2 \left(\left(\rho^{D*} \right)^2 \frac{\left(\Sigma^{D*} \right)^2}{\left(1 - \left(\rho^{D*} \right)^2 \right)} + \left(\Sigma^{D*} \right)^2 \right)$$

$$= \left(\epsilon_{\sigma*}^{\mu*} \right)^2 \frac{\left(\Sigma^{\sigma*} \right)^2}{\left(1 - \left(\rho^{\sigma*} \right)^2 \right)} + \left(\epsilon_{\sigma*}^{D*} \right)^2 \frac{\left(\Sigma^{D*} \right)^2}{\left(1 - \left(\rho^{D*} \right)^2 \right)}.$$

Provided that the shocks to σ^* and D^* are orthogonal, from (61) and (62), we have that following covariance between the change in the exchange rate and the change in the dollar liquidity ratio:

$$Cov(\Delta \log e^*, \Delta \log \mu^*) \approx \epsilon_{\sigma*}^{e*} \cdot \epsilon_{\sigma*}^{\mu*} \left(\left(\rho^{\sigma*} \right)^2 Var \left(\sigma^* \right) + \left(\Sigma^{\sigma*} \right)^2 \right) + \epsilon_{D*}^{e*} \cdot \epsilon_{D*}^{\mu*} \left(\left(\rho^{D*} \right)^2 Var \left(D^* \right) + \Sigma^{D*} \right)^2$$

$$= \epsilon_{\sigma*}^{e*} \cdot \epsilon_{\sigma*}^{\mu*} \left(\left(\rho^{\sigma*} \right)^2 Var \left(\sigma^* \right) + \left(\Sigma^{\sigma*} \right)^2 \right) + \epsilon_{D*}^{e*} \cdot \epsilon_{D*}^{\mu*} \left(\left(\rho^{D*} \right)^2 Var \left(D^* \right) + \Sigma^{D*} \right)^2$$

$$= \epsilon_{\sigma*}^{e*} \cdot \epsilon_{\sigma*}^{\mu*} \frac{\left(\Sigma^{\sigma*} \right)^2}{\left(1 - \left(\rho^{\sigma*} \right)^2 \right)} + \epsilon_{D*}^{e*} \cdot \epsilon_{D*}^{\mu*} \frac{\left(\Sigma^{D*} \right)^2}{\left(1 - \left(\rho^{D*} \right)^2 \right)}.$$

Thus, substituting the approximations to $Var \left(\Delta \log \mu^* \right)$ and $Cov(\Delta \log e^*, \Delta \log \mu^*)$ back into (60), we obtain that the univariate regression coefficient is approximately:

$$\beta_{\mu*}^{e*} \approx \frac{\epsilon_{\sigma*}^{e*} \cdot \epsilon_{\sigma*}^{\mu*} \cdot Var \left(\sigma^* \right) + \epsilon_{D*}^{e*} \cdot \epsilon_{D*}^{\mu*} Var \left(D^* \right)}{\left(\epsilon_{\sigma*}^{\mu*} \right)^2 Var \left(\sigma^* \right) + \left(\epsilon_{\sigma*}^{D*} \right)^2 Var \left(D^* \right)}.$$

$$= \frac{\epsilon_{\sigma*}^{e*}}{\epsilon_{\sigma*}^{\mu*}} \cdot \boldsymbol{w}^{\sigma*} + \frac{\epsilon_{D*}^{e*}}{\epsilon_{D*}^{\mu*}} \boldsymbol{w}^{D*}.$$

where:

$$w^{\sigma *} = \frac{\left(\epsilon_{\sigma *}^{\mu *}\right)^2 \frac{\left(\Sigma^{\sigma *}\right)^2}{1-\left(\rho^{\sigma *}\right)^2}}{\left(\epsilon_{\sigma *}^{\mu *}\right)^2 \frac{\left(\Sigma^{\sigma *}\right)^2}{\left(1-\left(\rho^{\sigma *}\right)^2\right)} + \left(\epsilon_{D *}^{\mu *}\right)^2 \frac{\left(\Sigma^{D *}\right)^2}{\left(1-\left(\rho^{D *}\right)^2\right)}} = \frac{\left(\epsilon_{\sigma *}^{\mu *}\Sigma^{\sigma *}\right)^2 \left(1-\left(\rho^{D *}\right)^2\right)}{\left(\epsilon_{\sigma *}^{\mu *}\Sigma^{\sigma *}\right)^2 \left(1-\left(\rho^{D *}\right)^2\right) + \left(\epsilon_{D *}^{\mu *}\Sigma^{D *}\right)^2 \left(1-\left(\rho^{\sigma *}\right)^2\right)}.$$

and

$$w^{D *} = \frac{\left(\epsilon_{D *}^{\mu *}\right)^2 \frac{\left(\Sigma^{D *}\right)^2}{\left(1-\left(\rho^{D *}\right)^2\right)}}{\left(\epsilon_{\sigma *}^{\mu *}\right)^2 \frac{\left(\Sigma^{\sigma *}\right)^2}{\left(1-\left(\rho^{\sigma *}\right)^2\right)} + \left(\epsilon_{\sigma *}^{D *}\right)^2 \frac{\left(\Sigma^{D *}\right)^2}{\left(1-\left(\rho^{D *}\right)^2\right)}} = \frac{\left(\epsilon_{\sigma *}^{\mu *}\Sigma^{\sigma *}\right)^2 \left(1-\left(\rho^{\sigma *}\right)^2\right)}{\left(\epsilon_{\sigma *}^{\mu *}\Sigma^{\sigma *}\right)^2 \left(1-\left(\rho^{D *}\right)^2\right) + \left(\epsilon_{D *}^{\mu *}\Sigma^{D *}\right)^2 \left(1-\left(\rho^{\sigma *}\right)^2\right)}.$$

D.6   Proof of Proposition (4)

Proof. **Part i**) Totally differentiating (38) with respect to P^* yields

$$d\mu^* = -\mu^* \left(\frac{dP^*}{P^*}\right). \tag{63}$$

The dollar liquidity premium is

$$R^b - (1 + i^{m,*}) \frac{P^*}{\mathbb{E}[P^*(X')]} = \mathcal{L}^*(\mu^*(P^*), P^*) \tag{64}$$

Totally differentiating (64) with respect to P^* and $(1 + i^{m,*})$, and using (63), we obtain

$$- R^{m,*} \left(\frac{dP^*}{P^*}\right) - \frac{P^*}{\mathbb{E}[P^*(X')]} d(1 + i^{m,*}) = -\mathcal{L}_{\mu *}^* \mu^* \left(\frac{dP^*}{P^*}\right) + \mathcal{L}_{P *}^* dP^* \tag{65}$$

where notice that $\mathbb{E}[P^*(X')]$ is constant because the shock is i.i.d. and $R^b = 1/\beta$.

Using $\mathcal{L}_{P *}^* = \frac{\mathcal{L}^*}{P^*}$ from Lemma 6, $R^b = R^{m,*} + \mathcal{L}^*$, and $\bar{R}^m = P^*(1 + i^{m,*})/\mathbb{E}[P^*(X')]$, and replacing these equalities in (65), we obtain:

$$\frac{d\log P^*}{d\log(1 + i^{m,*})} = -\frac{\bar{R}^m}{R^b - \mathcal{L}_{\mu *}^* \mu^*} \in (-1, 0) \tag{66}$$

where the sign follows from Lemma 6. The upper bound follows because $R^b > \bar{R}^m$.

Notice also that the euro bond premium remains constant, and so do P, μ and $\mathcal{L}$, as demonstrated in the proof of Proposition 1. This implies that $d\mathcal{L}^* = d\mathcal{DLP}$, $d\mathcal{L}_{\mu *}^* = d\mathcal{DLP}_{\mu *}$.

By the law of one price, we then have $\frac{d\log e^*}{d\log(1+i^{m,*})} = \frac{\bar{R}^m}{R^b - \mathcal{L}^*_\mu \mu^*}$ which implies an appreciation of the dollar.

Finally, we can rewrite (65) as

$$R^{m,*}\left(d\log e - d\log\left(1 + i^{m,*}\right)\right) = d\mathcal{L}^* = d\mathcal{DLP} < 0 \tag{67}$$

where the sign follows from the bounds on (66).

Part ii). When the shock is permanent, expected inflation is constant. From (18), it follows that the increase in $1 + i^{m,*}$ leads to a decrease in $\mathcal{L}^*$ and a reduction in $\mathcal{DLP}$. Total differentiation of (64) with respect to $1 + i^{m,*}$ and μ^* yields

$$-\bar{R}^{m,*}d\log(1 + i^{m,*}) = \mathcal{L}^*_\mu \mu^* d\log\mu^*, \tag{68}$$

and thus

$$\frac{d\log\mu^*}{d\log(1 + i^{m,*})} = -\frac{\bar{R}^{m,*}}{\mathcal{L}^*_{\mu^*}\mu^*} > 0. \tag{69}$$

where the sign follows from Lemma 6. Using that $d\log\mu^* = -d\log P^*$ when M^* and D^* are constant, we have from the law of one price that $\frac{d\log e^*}{d\log 1 + i^{m,*}} = \frac{\bar{R}^{m,*}}{-\mathcal{L}^*_\mu \mu^*}$. Finally

$$d\mathcal{DLP} = -\bar{R}^{m,*}d\log(1 + i^{m,*})$$

. □

Proofs of Proposition 5 (Open-Market Operations)

Preliminary Observations. We make two assumptions: first, deposits and securities are perfect substitutes, but the demand for the sum of deposits and securities is perfectly inelastic. Second, the supply of securities is fixed. Let $S^{H,*}$ indicate the household holding of dollar securities and $S^{G,*}$ the central bank's holdings of dollar securities. Thus, we have $S^{H,*} + S^{G,*} = S^*$ where S^* is a fixed supply of securities.

Consider a purchase of securities with reserves. The central banks' budget constraint in this case is modified to:

$$M_t^* + T_t^* + W_{t+1}^* + \left(1 + i_t^{d,*}\right) \cdot P_{t-1}^* S_{t-1}^{G,*} = P_t^* \cdot S_t^{G,*} + M_{t-1}^*(1 + i_t^{m,*}) + W_t^*(1 + i_t^{w,*}).$$

As in earlier proofs, we avoid time subscripts. Consider a small change in the holdings of

central bank securities purchased with reserves. We obtain:

$$dM^* = S^{G,*}dP^* + P^*dS^{G,*} = P^*S^{G,*}\frac{dP^*}{P^*} + P^*S^{G,*}\frac{dS^{G,*}}{S^{G,*}}. \tag{70}$$

Assuming that the central bank has a balance sheet such that Υ of its liabilities are backed with securities,

$$\Upsilon^* = \frac{P^*S^{G,*}}{M^*},$$

we modify (70) to obtain:

$$\frac{dM^*}{M^*} = \frac{P^*S^{G,*}}{M}\left(\frac{dP^*}{P^*} + \frac{dS^{G,*}}{S^{G,*}}\right) = \Upsilon^*\left(\frac{dP^*}{P^*} + \frac{dS^{G,*}}{S^{G,*}}\right).$$

Thus, expressed in logs, this condition is:

$$d\log M^* = \Upsilon^*\left(d\log P^* + d\log S^{G,*}\right). \tag{71}$$

The equation accounts for the fact that the growth in the money supply needed to finance the open-market operation has consider the change in the price level.

Next, since households are inelastic regarding the some of securities and deposits, it must be that $dD^* = -dS^{H,*}$. Since the supply of the security is fixed $-dS^{H,*} = dS^{G,*}$. Hence,

$$dD^* = dS^{G,*}.$$

Next, we express the change in the liquidity ratio in its differential form:

$$
\begin{aligned}
d\mu^* &= \mu^*\left(\frac{dM^*}{M^*} - \left(\frac{dP^*}{P^*} + \frac{dD^*}{D^*}\right)\right), \\
&= \mu^*\left(\frac{dM^*}{M^*} - \left(\frac{dP^*}{P^*} + \mu^*\Upsilon^*\frac{dS^{G,*}}{S^{G,*}}\right)\right),
\end{aligned}
$$

where the second line applies the definitions of μ^* and Υ^*.

In log terms, the last equation is:

$$d\log\mu^* = \left(d\log M^* - \left(d\log P^* + \Upsilon^*\mu^* \cdot d\log S^{G,*}\right)\right).$$

Substituting (71) we obtain:

$$
\begin{aligned}
d\log\mu^* &= \left(\Upsilon^*\left(d\log P^* + d\log S^{G,*}\right) - d\log P^* - \Upsilon^*\mu^* \cdot d\log S^{G,*}\right) \\
&= -\left(1 - \Upsilon^*\right)d\log P^* + \Upsilon^*\left(1 - \mu^*\right)\cdot d\log S^{G,*}.
\end{aligned}
\tag{72}
$$

Item (i). We now derive the main results. We follow the earlier proofs. Totally differentiating the liquidity premium with respect to μ^* and P^*, we obtain:

$$
\bar{R}^{m,*}d\log P^* + \mathcal{L}^*d\log P^* + \mathcal{L}^*_{\mu^*}\mu^*d\log\mu^* = 0.
\tag{73}
$$

Substituting (72) and collecting terms we obtain:

$$
\left(\bar{R}^{m,*} + \mathcal{L}^* - \left(1 - \Upsilon^*\right)\mathcal{LP}^*_{\mu^*}\mu^*\right)d\log P^* + \mathcal{L}^*_{\mu^*}\mu^*\Upsilon^*\left(1 - \mu^*\right)\cdot d\log S^{G,*} = 0.
\tag{74}
$$

Thus, we obtain:

$$
\frac{d\log P^*}{d\log S^{G,*}} = \frac{-\mathcal{LP}^*_{\mu^*}\mu^*\left(1 - \mu^*\right)\Upsilon^*}{R^b - \left(1 - \Upsilon^*\right)\mathcal{LP}^*_{\mu^*}\mu^*} > 0.
$$

If we substitute this expression in the left back into (72) we obtain:

$$
\frac{d\log\mu^*}{d\log S^{G,*}} = \frac{R^b\Upsilon^*\left(1 - \mu^*\right)}{R^b - \left(1 - \Upsilon^*\right)\mathcal{LP}^*_{\mu^*}\mu^*} > 0.
$$

Finally, by the law of one price:

$$
d\log e = -d\log P^* = \frac{\mathcal{L}^*_{\mu^*}\mu^*\left(1 - \mu^*\right)\Upsilon^*}{R^b - \left(1 - \Upsilon^*\right)\mathcal{L}^*_{\mu^*}\mu^*} < 0.
$$

Finally, the excess-bond premium and the dollar liquidity premium is:

$$
d\mathcal{L}^* = d\mathcal{DLP}^* = -R^{*,m}d\log P^* < 0.
$$

Item (ii). If the shock is permanent expected inflation does not change. Since nominal rates are fixed, we have that the dollar liquidity ratio must remain constant:

$$
d\log\mu^* = 0.
\tag{75}
$$

Moreover, $d\mathcal{BP}^* = d\mathcal{DLP}^* = 0$. From (72)

$$
\frac{d\log P^*}{d\log S^{G,*}} = \frac{\Upsilon^*}{\left(1 - \Upsilon^*\right)}\left(1 - \mu^*\right) > 0.
$$

By the law of one price then:

$$\frac{d \log e}{d \log S^{G,*}} = -\frac{d \log P^*}{d \log S^{G,*}} = -\frac{\Upsilon^*}{(1 - \Upsilon^*)} \left(1 - \mu^*\right).$$

E Microfoundations for Deposit Supplies and Loan Demands

Here we provide the micro-foundations for the loan demand and deposit supply schedules in a deterministic version of the model. We consider a representative global household. The household saves in dollar and euro deposits, supplies labor to an international firm, holds shares of this firm and owns a diversified portfolio of banks.

E.1 The Non-Financial Sector

Global household problem. The household enters the periods with a portfolio of dollar and euro deposits, denoted by $\{D_t, D_t^*\}$, holds shares of a global firm, Σ_t, and shares in a perfectly diversified portfolio of global banks, ϑ_t. These shares entitle the household to the firm's and bank's profits. The financial wealth available to the household (expressed in euros) is given by:

$$P_t n_t^h \equiv \left(1 + i_t^d\right) D_t + T_t + e_t \left(\left(1 + i_t^{*,d}\right) D_t^* + T_t^*\right) + P_t \left(q_t + r_t^h\right) \Sigma_t + P_t \left(Q_t + div_t\right) \vartheta_t \quad (76)$$

where T_t and T_t^* represent euro and dollar central bank transfers, q_t is the price of the firm (in terms of goods), r_t^h is the profit of the international firm, and Q_t is the price of the bank portfolio and div_t the dividend payout of banks.

In addition, the household supplies h_t hours that are remunerated at z_t euros per hour. The household uses its wealth to purchase deposits, to buy shares, and to consume. There are three types of consumption goods: dollar goods, denoted by c_t^*, euro goods, denoted by c_t, and a linear good, denoted by c_t^h. The household's budget constraint is:

$$e_t P_t^* c_t^* + P_t c_t + P_t c_t^h + D_{t+1} + e_t D_{t+1}^* + P_t q_t \Sigma_{t+1} + P_t Q_t \vartheta_{t+1} = P_t n_t^h + z_t h. \quad (77)$$

Both dollar and euro consumption are subject to deposit-in-advance (DIA) constraints:

$$c_t \leq \left(1 + i_t^d\right) \frac{D_t}{P_t}, \quad (78)$$

and

$$c_t^* \leq \left(1 + i_t^d\right) \frac{D_t}{P_t}. \quad (79)$$

The period utility is

$$U^* \left(c_t^*\right) + U \left(c_t\right) + c_t^h - \frac{h_t^{1+\nu}}{1+\nu},$$

where U^* and U are concave utility functions over both goods and $h_t^{1+\nu}/(1+\nu)$ is a labor dis-utility. To simplify the algebra of this section, we assume that $U^*_{c^*}(1) = U_c(1) = 1$.

The household's problem is:

$$V_t^h(D_t, D_t^*, \Sigma_t, \vartheta_t) = \max_{\left\{c_t, c_t^*, c_t^h, h_t, D_t, D_{t+1}^*, \Sigma_{t+1}, \vartheta_{t+1}\right\}} U^*(c_t^*) + U(c_t) + c_t^h - \frac{h_t^{1+\nu}}{1+\nu} \cdots$$
$$+ \beta V_{t+1}^h\left(D_{t+1}, D_{t+1}^*, \Sigma_{t+1}, \vartheta_{t+1}\right) \quad (80)$$

subject to the budget constraint (77 and 76) and the two DIA constraints (78-79).

Firm Problem. The firm produces all goods in the economy using the same production function

$$y_t = A_{t+1} h_t^\alpha.$$

The firm's output is divided into:

$$c_t^* + c_t + c_t^h = y_t. \quad (81)$$

The firm revenues come from selling goods in the dollar, euro, and linear good markets:

$$e_t P_t^* c_t^* + P_t c_t + P_t c_t^h = P_t y_t.$$

To produce positive amounts of all goods, the firm must be indifferent between selling in either market. Hence, the law of one price will hold in an equilibrium with positive consumption of all goods—the Inada conditions guarantee this is the case.

To maximize profits, the firm chooses borrowed funds B_{t+1}^d and labor h_t. The demand for loansemerges from a working capital constraint: $z_t h_t \leq B_{t+1}^d$. The firm saves in deposits whatever borrowings it doesn't spend in wages.

The firm's problem is given by:

$$
\begin{aligned}
P_{t+1} r_{t+1}^h &= \max_{B_{t+1}^d \geq 0, h_t \geq 0} P_{t+1} A_{t+1} h_t^\alpha - \left(1 + i_{t+1}^b\right) B_{t+1}^d + \left(1 + i_{t+1}^d\right)\left(B_{t+1}^d - z_t h_t\right) \\
&= \max_{B_{t+1}^d \geq 0, h_t \geq 0} P_{t+1} A_{t+1} h_t^\alpha - \left(1 + i_{t+1}^b\right) z_t h_t - \left(i_{t+1}^b - i_{t+1}^d\right)\left(B_{t+1}^d - z_t h_t\right). \quad (82)
\end{aligned}
$$

Equilibrium. In the body of the paper we characterized the equilibrium in loan and deposit markets, taking as given the loan demand and deposit supply schedules, and the transfers rules. In addition to these financial markets, the non-financial sector features a labor market, firm shares market, bank shares market, and the three goods markets. Next, we derive the

loan demand and deposit supply schedules and comment on how once these asset markets clear, all other markets clear.

E.2   Derivation of Deposit Supply and Loan Demand

Step 1 - deposit demand. We clear the linear good, c_t^h, from the household's budget constraint:

$$c_t^h = \frac{P_t n^h + z_t h - \left(e_t P_t^* c^* + P_t c + D_{t+1} + e_t D_{t+1}^* + P_t\left(r_t + q_t\right)\Sigma_t + P_t\left(Q_t + div_t\right)\vartheta_t\right)}{P_t}$$

$$= n^h + \frac{z_t}{P_t}h_t - \left(c_t^* + c_t + \left(r_t + q_t\right)\Sigma_t + \left(Q_t + div_t\right)\vartheta_t + \frac{D_{t+1}}{P_t} + \frac{D_{t+1}^*}{P_t^*}\right). \quad (83)$$

where the second line uses the law of one price.

Substituting (83) into the objective of the household's problem (80) we obtain:

$$V_t^h\left(D_t, D_t^*, \Sigma_t, \vartheta_t\right) = n_t^h + \max_{\left\{c_t, c_t^*, h_t, D_t, D_{t+1}^*, \Sigma_{t+1}, \vartheta_{t+1}\right\}} U^*\left(c_t^*\right) + U\left(c_t\right) - \frac{h_t^{1+\nu}}{1+\nu}\cdots$$

$$+ \frac{z_t}{P_t}h_t - \left(c_t^* + c_t + \left(r_t + q_t\right)\Sigma_t + \left(Q_t + div_t\right)\vartheta_t + \frac{D_{t+1}}{P_t} + \frac{D_{t+1}^*}{P_t^*}\right)\cdots$$

$$+ \beta V_{t+1}^h\left(D_{t+1}, D_{t+1}, \Sigma_{t+1}, \vartheta_{t+1}\right)$$

subject to the two DIA constraints (78-79).

We proceed to obtain the deposit supply.

Since $\left\{D_{t+1}, D_{t+1}^*\right\}$ enter symmetrically, we derive the deposit supply only for one currency. We take the first-order condition with respect to c_t and notice that if the DIA constraint does not bind, $U_c\left(c\right) = 1$. In turn, if the deposit in advance constraint indeed binds, then:

$$c = \left(1 + i_t^d\right)\frac{D_t}{P_t} = \frac{\left(1 + i_t^d\right)}{P_t/P_{t-1}}\frac{D_t}{P_{t-1}} = R_t^d\frac{D_t}{P_{t-1}}.$$

Thus, we can combine both cases, with and without the binding DIA constraint, to write down the optimal consumption rule:

$$c = \min\left\{\left(U_c\right)^{-1}\left(1\right), R_t^d \cdot \frac{D_t}{P_{t-1}}\right\}. \quad (84)$$

By analogy:

$$c^* = \min\left\{\left(U_{c^*}^*\right)^{-1}\left(1\right), R_t^{d,*} \cdot \frac{D_t^*}{P_{t-1}^*}\right\}.$$

It is convenient to treat c and c^* directly as functions of $\frac{D}{P_{t-1}}$ and $\frac{D^*}{P^*_{t-1}}$ in the next step.

Step 2 - deposit supply schedules. We replace the optimal euro and dollar consumption rules into the objective. We have:

$$
\begin{aligned}
V_t^h \left(D_t, D_t^*, \Sigma_t, \vartheta_t \right) \; = \;\; & n^h + \max_{\left\{ c_t, c_t^*, h_t, D_t, D_{t+1}^*, \Sigma_{t+1}, \vartheta_{t+1} \right\}} U^* \left(\min \left\{ (U_{c^*}^*)^{-1} (1), R_t^{d,*} \cdot \frac{D^*}{P^*_{t-1}} \right\} \right) \cdots \\
& + \;\; U \left(\min \left\{ (U_c)^{-1} (1), R_t^d \cdot \frac{D_t}{P_{t-1}} \right\} \right) - \frac{h^{1+\nu}}{1+\nu} \cdots \\
& + \;\; n^h + \frac{z_t}{P_t} h - \min \left\{ (U_{c^*}^*)^{-1} (1), R_t^{d,*} \cdot \frac{D_t^*}{P^*_{t-1}} \right\} \cdots \\
& - \;\; \min \left\{ (U_c)^{-1} (1), R_t^d \cdot \frac{D_t}{P_{t-1}} \right\} \cdots \qquad\qquad\qquad (85) \\
& - \;\; \left((r_t + q_t) \Sigma_t + (Q_t + div_t) \vartheta_t + \frac{D_{t+1}}{P_t} + \frac{D_{t+1}^*}{P_t^*} \right) \cdots \\
& + \;\; \beta V_{t+1}^h \left(D_{t+1}, D_{t+1}, \Sigma_{t+1}, \vartheta_{t+1} \right). \qquad\qquad\qquad (86)
\end{aligned}
$$

Next, we the derive deposit demand: We take the first-order conditions with respect to D_{t+1}/P_t to obtain:

$$
1 \; = \; \beta \frac{\partial V_{t+1}^h}{\partial \left(D_{t+1}/P_t \right)}. \qquad\qquad (87)
$$

Next, we derive the envelope condition. We have two cases.

Case 1: binding DIA constraint the following period. For the case where

$$
R_t^d \cdot D_t / P_{t-1} < 1
$$

we have from (86) that:

$$
\frac{\partial V_t^h}{\partial \left(D_t/P_{t-1} \right)} = U_c R_t^d - R_t^d + R_t^d = U_c R_t^d.
$$

Case 1: non-binding DIA constraint the following period. For the case where $R_{t-1}^d \frac{D}{P_{t-1}} \geq 1$, we have from (86) that

$$
\frac{\partial V_t^h}{\partial \left(D_t/P_{t-1} \right)} = R_t^d.
$$

Thus, combining the two envelope conditions we obtain:

$$
\frac{\partial V_t^h}{\partial \left(D_t/P_{t-1} \right)} = \begin{cases} U_c \left(R_t^d \cdot D_t/P_{t-1} \right) R_t^d & \text{for } R_t^d \cdot D_t/P_{t-1} < 1 \\ R_t^d & \text{otherwise.} \end{cases} \tag{88}
$$

We shift (88) one period forward and substitute in (87) in the left-hand side to obtain:

$$
\frac{1}{\beta} = \begin{cases} U_c \left(R_{t+1}^d \cdot D_{t+1}/P_t \right) R_{t+1}^d & R_{t+1}^d \cdot D_t/P_{t-1} < 1 \\ R_{t+1}^d & \text{otherwise.} \end{cases}
$$

In the body of the paper, using the banks' problem, we show that $R_{t+1}^d < R^b = 1/\beta$. Thus, the only relevant portion to determine the demand condition is the one where there's no satiation of deposits. We hence, will only use this portion.

We now adopt power utility. Assume that $U = c^{1-\gamma}/\left(1-\gamma\right)$ and $U^* = (c^*)^{1-\gamma^*}/\left(1-\gamma^*\right)$. Then,

$$
\frac{1}{\beta} = \left(R_{t+1}^d \cdot D_{t+1}/P_t \right)^{-\gamma} R_{t+1}^d.
$$

We clear D/P_t to obtain the euro deposit supply schedule:

$$
D_{t+1}/P_t = \beta^{1/\gamma} \left(R_{t+1}^d \right)^{\frac{1-\gamma}{\gamma}}.
$$

By analogy, we have the dollar supply schedule:

$$
D_{t+1}^*/P_t^* = \beta^{1/\gamma^*} \left(R_{t+1}^{*,d} \right)^{\frac{1-\gamma^*}{\gamma^*}}.
$$

More generically, following the same states, if we introduce preference shocks to the utility specifications, as follows:

$$
U_t = (c/x_t)^{1-\gamma}/\left(1-\gamma\right) \text{ and } U_t^* = (c^*/x_t^*)^{1-\gamma^*}/\left(1-\gamma^*\right),
$$

the demand schedules generalize to:

$$
D_{t+1}/P_t = x_t \beta^{1/\gamma} \left(R_t^d \right)^{\frac{1-\gamma^x}{\gamma^x}}.
$$

By analogy, we have that

$$
D_{t+1}^*/P_t^* = x_t^* \beta^{1/\gamma} \left(R_t^d \right)^{\frac{1-\gamma^x}{\gamma^x}}.
$$

We obtain this conditions following exactly the same steps.

All in all, the demand schedules are akin to those in the body of the paper, where the reduced form coefficients are given by:

$$\Theta_t^d = x_t \beta^{1/\gamma^d} \text{ and } \epsilon^d = \frac{1}{\gamma^d} - 1,$$

and

$$\Theta_t^{*,d} = x_t^* \beta^{1/\gamma^{*,d}} \text{ and } \epsilon^{*,d} = \frac{1}{\gamma^{*,d}} - 1.$$

Next, we describe the labor supply schedule.

Step 3 - labor supply. The first-order condition with respect to h in the household's problem yields a labor supply that only depends on the real wage:

$$h_t^\nu = z_t/P_t. \tag{89}$$

Next, we move to the firm's problem to obtain the labor demand.

Step 4 - labor demand. Since from the bank's problem, it will be the case that $i_{t+1}^b > i_{t+1}^d$, then the working capital constraint in (82) is binding, $z_t h_t = B_{t+1}^d$. Thus, the firm's objective is to

$$\max_{h_t \geq 0} P_{t+1} A_{t+1} h_t^\alpha - \left(1 + i_{t+1}^b\right) z_t h_t.$$

The first-order condition for labor h_t yields:

$$P_{t+1} \alpha A_{t+1} h_t^\alpha = \left(1 + i_{t+1}^b\right) z_t h_t.$$

Dividing both sides by P_t, we obtain

$$\frac{P_{t+1}}{P_t} \alpha A_{t+1} h_t^\alpha = \left(1 + i_{t+1}^b\right) \frac{z_t}{P_t} h_t. \tag{90}$$

Step 5 - loan demand. Next, we use the labor supply (89) and labor demand (90), to solve for labor as a function of the loans rate:

$$\frac{P_{t+1}}{P_t} \alpha A_{t+1} h_t^\alpha = \left(1 + i_{t+1}^b\right) h_t^{\nu+1} \rightarrow R_t^b = \frac{\alpha A_{t+1} h_t^\alpha}{h_t^{\nu+1}}. \tag{91}$$

Since the working capital constraint binds:

$$\frac{B_{t+1}^d}{P_t} = h_t \frac{z_t h_t}{P_t} = h_t^{\nu+1} \rightarrow h_t = \left(\frac{B_{t+1}^d}{P_t}\right)^{\frac{1}{\nu+1}}. \tag{92}$$

Thus, we can combine (91) and (92) to obtain the loans demand:

$$R_t^b = \alpha A_{t+1} \left(\frac{B_{t+1}^d}{P_t}\right)^{-1} \left(\frac{B_{t+1}^d}{P_t}\right)^{\frac{\alpha}{\nu+1}} \rightarrow \frac{B_{t+1}^d}{P_t} = \Theta_t \left(R_{t+1}^b\right)^{\epsilon^b}, \qquad (93)$$

where the reduced form coefficients of the loans demand are:

$$\Theta_t^b = (\alpha A_{t+1})^{-\epsilon^b} \text{ and } \epsilon^b = \left(\frac{\nu+1}{\alpha-(\nu+1)}\right).$$

Step 6 - output, firm value and bank values. We replace the loans demand (93) into (92) to obtain the equilibrium labor as a function of the equilibrium loans rate:

$$h_t = \left(\frac{1}{\alpha A_{t+1}}\right)^{\frac{1}{\alpha-(\nu+1)}} \left(R_{t+1}^b\right)^{\frac{1}{\alpha-(\nu+1)}}.$$

We replace (92) into the production function to obtain:

$$y_{t+1} = A_{t+1} \left(\frac{1}{\alpha A_{t+1}}\right)^{\frac{\alpha}{\alpha-(\nu+1)}} \left(R_{t+1}^b\right)^{\frac{\alpha}{\alpha-(\nu+1)}} \rightarrow y_{t+1} = \left(\frac{1}{\alpha}\right)^{\frac{\alpha}{\alpha-(\nu+1)}} A_{t+1}^{\frac{(\nu+1)}{\nu+1-\alpha}} \left(R_{t+1}^b\right)^{\frac{\alpha}{\alpha-(\nu+1)}}.$$

The profit of the international firm is given by:

$$r_{t+1}^h = y_{t+1} - R_{t+1}^b B_{t+1} \rightarrow r_{t+1}^h = A_{t+1}^{\frac{(\nu+1)}{\nu+1-\alpha}} \left(\alpha^{-\frac{\alpha}{\alpha-(\nu+1)}} - \alpha^{-\frac{\nu+1}{\alpha-(\nu+1)}}\right) \cdot \left(R_{t+1}^b\right)^{\frac{\alpha}{\alpha-(\nu+1)}}.$$

The price of the firm is given by the first-order condition with respect to Σ. In that case, q_t must satisfy:

$$q_t = \beta \left(r_{t+1}^h + q_{t+1}\right) \rightarrow q_t = \sum_{\tau \geq 1} \beta^\tau \left(r_{t+\tau}^h\right).$$

With this, we conclude that output, hours, and the firm price are decreasing in current (and future) loans rate.

Finally, consider the price of the bank's shares. By the same token,

$$Q_t = \beta \left(div_t + Q_{t+1}\right),$$

Multiply both sides by $1/\beta$ and recall that $\vartheta_t = 1$. Thus, we have:

$$\frac{1}{\beta} Q_t = \left(div_t + \beta \frac{1}{\beta} Q_{t+1}\right).$$

By change of variables let $v_t \equiv \frac{1}{\beta} Q_t$. Therefore, the value of the firm is given by

$$v_t = div_t + \beta v_{t+1}.$$

Solving this condition from time zero implies that:

$$v_0 = \sum_{t \geq 0} \beta^t div_t.$$

Thus, the bank's objective in the body of the paper is consistent with maximizing the bank's value.

Remark. We priced the firms and banks so that they are held in equilibrium by households. Thus, the shares markets clear. Note that throughout the proof we use the labor market-clearing condition, (91). Hence, the labor market clears. Since in the body of the paper we deal with clearing in the loans and deposit markets, by Walras's law, this implies clearing in the three goods markets.

All in all, the equilibrium in the banking block is an autonomous system. As long as the loan and deposit markets clear, we have clearing in the non-financial sector: Once we compute equilibria taking the schedules as exogenous in the bank's problem, we obtain output and household consumption from the equilibrium loan and deposit rates.

Finally, we should note that in presence of aggregate risk (inflation risk in particular), the deposit demand schedules will feature a risk premium that we are not considering in the derivation. We ignore this terms.

F Computational Algorithms

Steady State: equilibrium conditions. We solve the steady-state of the model where $n = 0$ every period.[30] Solving for steady-state equilibrium requires requires to solve for 11 variables, three interest rates, $\{R^{*,d}, R^d, R^b\}$, three prices $\{P, P^*, e\}$ and five quantities $\{m^*, m, d, d^*, b^*\}$. We summarize these conditions below and show that the system .

Prices given quantities are given by:

$$d^* = \Theta^{*,d} \left(R^{*,d}\right)^{\epsilon^{d^*}} \tag{94}$$

$$d = \Theta^d \left(R^d\right)^{\epsilon^d} \tag{95}$$

and

$$b^* = \Theta^b \left(R^b\right)^{\epsilon^b}. \tag{96}$$

The two prices are given by the equilibrium in the market for real dollar reserves,

$$m^* = \frac{M^*}{P^*}. \tag{97}$$

and by the equilibrium in the market for real euro reserves is for euro reserves:

$$m = \frac{M}{P}. \tag{98}$$

In turn, the exchange rate is obtained via the law of one price:

$$e = P/P^*.$$

Finally, we have four first-order conditions and the budget constraint to pin down the quantities:

a) the dollar liquidity premium:

$$R^{m,*} + \mathbb{E}\left[\chi^*_{m^*}\right] = R^m + \mathbb{E}\left[\chi_m\right]$$

b) the bond premium:

$$R^b = R^{m,*} + \mathbb{E}\left[\chi^*_{m^*}\right] \tag{99}$$

---

[30]When $n > 0$, $R^b = 1/\beta$ so we drop one variable and the budget constraint.

c-d) the two deposit premia

$$R^{d,*} + \mathbb{E}\left[\chi_{d*}^*\right] = R^{m,*} + \mathbb{E}\left[\chi_{m*}^*\right] \tag{100}$$

and

$$R^{d,*} + \mathbb{E}\left[\chi_{d*}^*\right] = R^{m,*} + \mathbb{E}\left[\chi_{m*}^*\right] \tag{101}$$

Finally, the budget constraint for $n = 0$ is:

$$b + m + m^* = d + d^*.$$

This is a system of 11 equations and 11 unknowns. Next, show how to solve the model in ratios.

Steady State: solving the model in ratios. Recall that liquidity ratios are given by:

$$\mu \equiv \frac{m}{d} \text{ and } \mu^* \equiv \frac{m^*}{d^*}.$$

We define the ratio of real euro to dollar funding as:

$$\upsilon \equiv \frac{d}{d^*}.$$

Once we obtain $\{d^*, \upsilon, \mu, \mu^*\}$, we obtain $\{m, m^*, d\}$ from these three definitions.

We have shown that the interbank market tightness in euros and dollars are given by:

$$\theta\left(\mu\right) = \max\left\{-\frac{\int_{-\infty}^{-\mu}\left(\mu + \omega\right) \cdot d\Phi\left(\omega\right)}{\int_{-\mu}^{\infty}\left(\mu + \omega\right) \cdot d\Phi\left(\omega\right)}, 0\right\}$$

and

$$\theta^*\left(\mu^*\right) = \left\{-\frac{\int_{-\infty}^{-\mu^*}\left(\mu^* + \omega\right) \cdot d\Phi^*\left(\omega^*\right)}{\int_{-\mu^*}^{\infty}\left(\mu + \omega\right) \cdot d\Phi^*\left(\omega^*\right)}, 0\right\}.$$

Thus we have introduced three ratios. Notice that once we obtain $\{\mu, \mu^*\}$ we obtain $\{d, d^*\}$. Once we obtain υ, we have $\{e^{-1}\}$.

Furthermore, the budget constraint written in ratios is:

$$b^* = \left(\upsilon\left(1 - \mu\right) + \left(1 - \mu^*\right)\right)d^*. \tag{102}$$

We substitute out $\{R^b, R^d, R^{*,d}\}$ and work directly with the market clearing conditions.

We replace b^* from the budget constraint. If we substitute the ratios $\{\mu^*, \mu, \upsilon, d^*\}$ into the equilibrium conditions and, thus only have one quantity variable d^*, and the rest of the system is expressed in ratios.

Steady State: autonomous sub-system. We solve for $\{\mu^*, \mu, \upsilon, d^*\}$ using:

1) Bond premium:

$$\Theta^b \left((\upsilon (1 - \mu) + (1 - \mu^*)) d^* \right)^{\epsilon^b} = R^{*,m} + \mathbb{E} \left[\chi_m (\mu^*) \right]. \tag{103}$$

2) The dollar liquidity premium:

$$R^m + \mathbb{E} \left[\chi_m (\mu) \right] = R^{*,m} + \mathbb{E} \left[\chi_m (\mu^*) \right].$$

3) The euro funding premium:

$$\Theta^d (\upsilon d^*)^{-\epsilon^d} + \mathbb{E} \left[\chi_d (\mu) \right] = R^{*,m} + \mathbb{E} \left[\chi_m (\mu^*) \right] \tag{104}$$

4) dollar funding premium:

$$\Theta^{*,d} (d^*)^{-\epsilon^{d*}} + \mathbb{E} \left[\chi_{d^*} (\mu^*) \right] = R^{*,m} + \mathbb{E} \left[\chi_{m^*} (\mu^*) \right]. \tag{105}$$

These four equations provide us with a solution to $\{d^*, \nu, \mu, \mu^*\}$.

Steady State: Solving the rest of the model. With the solution to $\{\mu^*, \mu, \upsilon, d^*\}$ we obtain $\{m^*, m, d\}$ using:

$$m = \mu d, \ m^* = \mu^* d^*, \ \text{and} \ d = \nu d^*.$$

Then, we obtain the euro price from

$$P = \frac{M}{\mu \upsilon d^*},$$

the dollar price from

$$P^* = \frac{M^*}{\mu^* d^*},$$

and the exchange rate from

$$e = \frac{P}{P^*}.$$

F.1 Algorithm to obtain a Global Solution

Define $X \in \mathcal{X} = \{1, 2, 3, \ldots, N^s\}$ to be a finite set of states. We let X follow a Markov process with transition matrix Q. Thus, $X' \sim Q(X)$. That is, at each period, $X = \{\sigma^*, \sigma, i^{*,m}, i^m, M, M^*, \Theta^d, \Theta^{*,d}\}$ are all, potentially, functions of the state X.

The algorithm proceeds as follows. We define a "greed" parameter Δ^{greed} and a tolerance parameter ε^{tol}, and construct a grid for $\mathcal{X}$. We conjecture a price-level functions $\{p_{(0)}(X), p^*_{(0)}(X)\}$ which produces a price levels in both currencies as a function of the state. As an initial guess, we use $p_{(0)}(X) = p^*_{ss}$, and $p^*_{(0)}(X) = p^*_{ss}$ setting the exchange rate to its steady state level in all periods. We proceed by iterations, setting a tolerance count tol to $tol > 2 \cdot \varepsilon^{tol}$.

Outerloop 1: Iteration of price functions. We iterate price functions until they converge. Let n be the $n - th$ step of a given iteration. Given a $p_{(n)}(X), p^*_{(n)}(X)$, we produce a new price level functions $p_{(n+1)}(X), p^*_{(n+1)}(X)$ if $tol > \varepsilon^{tol}$.

Innerloop 1: Solve for real policy rates. For each X in the grid for $\mathcal{X}$, we solve for

$$\left\{\bar{R}^m(X), \bar{R}^{*,m}(X), \bar{R}^w(X), \bar{R}^{*,w}(X)\right\}.$$

Let j be the $j - th$ step of a given iteration. Conjecture values

$$\left\{\bar{R}^m_{(0)}(X), \bar{R}^{*,m}_{(0)}(X), \bar{R}^w_{(0)}(X), \bar{R}^{*,w}_{(0)}(X)\right\}$$

We use $\left\{\bar{R}^m_{ss}, \bar{R}^{*,m}_{ss}, \bar{R}^w_{ss}, \bar{R}^{*,w}_{ss}\right\}$ as an initial guess. We then update

$$\left\{\bar{R}^m_{(j)}(X), \bar{R}^{*,m}_{(j)}(X), \bar{R}^w_{(j)}(X), \bar{R}^{*,w}_{(j)}(X)\right\}$$

until we obtain convergence:

2.a Given this guess, we solve for the liquidity ratios in Dollars and Euro $\{\mu, \mu^*, \bar{R}^d, \bar{R}^{*,d}\}$ as a function of the state using:

$$\bar{R}^d + \frac{1}{2}\left(\chi^+(\mu) - \chi^-(\mu)\right) = \bar{R}^{*,d} + \frac{1}{2}\left(\chi^{*,+}(\mu^*) - \chi^{*,-}(\mu^*)\right)$$

$$\bar{R}^m + \frac{1}{2}\left(\chi^+(\mu) + \chi^-(\mu)\right) = \bar{R}^{*,m} + \frac{1}{2}\left(\chi^{*,+}(\mu^*) + \chi^{*,-}(\mu^*)\right)$$

$$\Theta^b\left((\upsilon(1-\mu) + (1-\mu^*))d^*\right)^{\epsilon^b} = \bar{R}^{*,d} + \frac{1}{2}\left(\chi^+(\mu) - \chi^-(\mu)\right)$$

$$\bar{R}^m = \bar{R}^{*,d} + \frac{1}{2}\left(\chi^+(\mu) - \chi^-(\mu)\right) - \frac{1}{2}\left(\chi^+(\mu) + \chi^-(\mu)\right).$$

This step yields an update for $\left\{R^d(X), R^{*,d}(X)\right\}$.

2.b Given the solutions to $\left\{R^d(X), R^{*,d}(X)\right\}$, we solve $\{d^*, v\}$ using:

$$d^* = \left[\frac{\bar{R}^{*,d}}{\Theta^{*,d}}\right]^{1/\epsilon^{d*}}$$

$$v = \left[\frac{\bar{R}^d}{\Theta^d}\right]^{1/\epsilon^d}\left[\frac{\bar{R}^{*,d}}{\Theta^{*,d}}\right]^{1/\epsilon^{d*}}.$$

This step yields an update for $\{d^*(X), v(X)\}$.

2.c Given $\{d^*(X), v(X)\}$ we solve for prices $\{p, p^*, e\}$ using:

$$\mu v d^* = \frac{M}{p}$$

$$\mu^* d^* = \frac{e}{p}M^*$$

$$p^* = e^{-1}p.$$

2.d Finally, we update the real policy rates. For that we construct the expected inflation in each currency:

$$\mathbb{E}\left[\pi^*\right] = \frac{\sum_{s'\in S}Q(s'|s)\,p_{(n)}^*(s)}{p^*(s)}$$

and

$$\mathbb{E}\left[\pi\right] = \frac{\sum_{s'\in S}Q(s'|s)\,p_{(n)}(s)}{p(s)}.$$

We then update the policy rates by:

$$R_{(j+1)}^{*,a} = \frac{(1+i^{*,a})}{(1+\pi^*)}\ \text{for}\ a\in\{m,w\}$$

and

$$R_{(j+1)}^a = \frac{(1+i^a)}{(1+\pi)}\ \text{for}\ a\in\{m,w\}.$$

2.e Repeat steps 2.a-2.d, unless

$$\left\{ R_{(j)}^m (X), R_{(j)}^{*,m} (X), R_{(j)}^w (X), R_{(j)}^{*,w} (X) \right\}$$

is close to

$$\left\{ R_{(j+1)}^m (X), R_{(j+1)}^{*,m} (X), R_{(j+1)}^w (X), R_{(j+1)}^{*,w} (X) \right\}.$$

If the real policy rates have converged, update prices according to

$$p_{(n+1)}^* (X) = \Delta^{greed} p^* + \left(1 - \Delta^{greed} \right) p_{(n)}^* (X)$$

and

$$p_{(n+1)} (X) = \Delta^{greed} p + \left(1 - \Delta^{greed} \right) p_{(n)}^* (X)$$

and proceed back to the outer-loop.