Preferred Habitat, Policy, and the CIP Puzzle

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Abstract

We examine the recent failure of covered interest parity and the emergence of a substantial cross-currency basis. We link this to international policy transmission in the context of intermediation frictions and market segmentation. Our framework combines preferred habitat theory of fixed income pricing with theories of bounded arbitrage on FX swap markets. The model highlights the interplay between policy, risk, and structural factors and shows how market segmentation leads to a volatility premium that endogenously contributes to intermediation frictions. We test our model with daily data on USD/EUR cross currency basis swap rates of different maturities, policy rate futures and policy attention indices based on Google search data in an EGARCH-in-mean framework. Our estimates show that, after accounting for conditional volatility, CIP deviations are caused by a combination of policy and risk factors. In particular, we find strong and significant GARCH-in-Mean effects as well as policy effects in both, means and variances. This supports the presence of a volatility channel of policy transmission. The term structure of cross-currency basis swap rates further exposes different dynamics on money and capital markets. Our findings highlight the consideration of risk- and policy factors in conjunction with structural intermediation factors in explaining the CIP puzzle.

1 Introduction

In recent years, a crucial no-arbitrage condition in international macroeconomics, the covered interest parity (CIP) condition, has failed. CIP requires that on foreign exchange markets interest rate differentials translate into differences between spot and forward exchange rates, closing otherwise existing arbitrage opportunities. [Akram et al. (2008)] documented the existence of frequent CIP violations pre 2008, but those were generally short-lived and arbitrage opportunities hence quickly closed. However, over the last decade CIP deviations have become persistent, which appeared to violate this no-arbitrage constraint.

Early contributions investigating this CIP failure highlight risk factors, which was plausible given the preceding great financial crisis (GFC). [Coffey et al. (2009)] link this to a mixture of adverse funding conditions and heightened counterparty risk.

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following the GFC. They attribute a significant role of an observed reversal of the
disequilibrium to coordinated monetary policies, such as swap-agreements. [Gabaix and Maggiori (2015)] propose a theoretical framework, integrating financial frictions in a general equilibrium model of exchange rate determination. Here financial intermediaries’ limited risk bearing capacity constitutes a mark-up over marginal costs, resulting in CIP deviations. But [Avdjiev et al. (2016)] and [Du et al. (2017)] observe a return of CIP violations post 2014 in a comparatively low-risk environment. This suggests that risk factors alone are insufficient in explaining CIP failure. This widening of cross-currency basis swap rates (CCBS), a common measure for the degree of CIP failure, in a relatively calm risk environment post GFC is often referred to as the CIP puzzle.

There are several explanations in the literature attempting to tackle this conundrum. [Du et al. (2017)] highlight the role of financial intermediation costs, such as balance sheet costs and end of quarter effects, which are arising from changes in the regulatory framework post GFC. This is particularly important as it offers an explanation for the persistence of observed CCBS movements and also gives evidence for causes of CIP failure. [Avdjiev et al. (2016)] investigate the relationship between the external value of the US dollar, CIP violations and cross-border USD denominated bank-lending. They find a positive relationship between USD appreciations and CIP deviations, which, as Du et al., they attribute to banks’ costs of USD-denominated balance sheet exposure. [Sushko et al. (2017)] include these observed frictions in a model bounded arbitrage on swap markets. Here, CCBS are a function of hedging demand and market-structural factors such as banks’ ability do raise funding on repo-markets and market liquidity. In this framework, a cross-currency basis opens due to hedging demand-shocks, most notably monetary policy induced rate-compression, which then persists due to market-structural factors implying intermediation costs on swap markets. Empirically, they find significant impacts of both, a proxy for hedging demand and structural factors, on the short term (2 month) JPY/USD basis and of hedging demand only on the equivalent long-term (2 year) cross-currency basis. Using a panel of several different freely floating currencies largely validates results, albeit less robustly. [Rime et al. (2016)] investigate money-market CCBS rates, finding that risk-less CIP arbitrage opportunities exist for large international banks only. Money market cross currency bases mainly arise from differences in arbitrageurs’ access to funding liquidity, which has been greatly affected by the shift from collateralised (repo) funding to unsecured funding markets post GFC, which only large international banks could access at competitive marginal costs.

Whilst the arguments on financial intermediation costs, particularly balance sheet costs, on swap markets as driver of the persistence of CIP violations, and that of regulatory factors having a causal impact are convincing, they do not entirely explain the dynamics of CCBS rates observed in recent years. Arguably a sizeable impact on bank balance sheets, and hence balance sheet costs, has been through monetary policy. Similarly, one would expect policy to have an effect on banks’ refunding operations and hence money market arbitrage. However, there are relatively few contributions explicitly investigating the impact of the global policy environment on swap markets. The recent disequilibrium on foreign exchange swap markets succeeds rounds of unprecedented global monetary expansions, which were largely dominated by unconventional policies, such as large scale asset purchases. Whilst the initial policy reaction to the GFC was relatively coordinated globally,
policy has more recently become increasingly asymmetric. This begs the question on the impact of policy asymmetries on FX swap market frictions.

Unconventional monetary policies have been discussed extensively in the recent literature. One characteristic of such policies is that they are ineffective in traditional general equilibrium frameworks such as Christiano et al. (2005) and Smets and Wouters (2003). In particular traditional DSGE models fail to produce sufficiently large term spreads on the fixed income market (Rudebusch and Swanson 2008). This initiated a large body of literature addressing the impact of financial frictions on policy transmission. One source of such frictions lies in the existence of market segmentation and hence failure of the expectations theory of the term structure. Seminal papers on market segmentation can be found in Krishnamurthy and Vissing-Jorgensen (2007) and Krishnamurthy and Vissing-Jorgensen (2011). Vayanos and Vila (2009) formalise market segmentation in a preferred-habitat theory of the fixed income market. One crucial element of such preferred habitat models is to assume different agents: preferred habitat investors, whose demand is focussed on particular market segments, and arbitrageurs, who exploit and thereby mitigate segmentation through optimising an arbitrage portfolio subject to risk. This implies arbitrageurs have a limited risk-bearing capacity, which in turn implies that in segmented markets risk affects returns and hence has repercussions for policy-making. It is therefore the combination of preferred habitats and transaction costs in form of risk, which is affecting arbitrageurs’ ability to mitigate market segmentation, that introduces frictions. This is often referred to as the risk-premium channel of monetary transmission. However, most term-structure models suffer from assuming market segmentation only along the term-dimension, which is ignoring credit risk. Altavilla et al. (2015) address this, proposing a preferred habitat model allowing for a credit channel. Investigating ECB’s asset purchase program with high-frequency event studies, they find ECB announcements having significantly lowered yields even in times of low financial distress. Controlling for the timing of announcements attributes this effect to the composition of asset purchases, which gives rise to broader transmission channels and emphasises the role of arbitrageurs’ limited risk-bearing capacity.

An empirical consequence of preferred habitat theory is impact of time varying volatility, which is crucial as arbitrageurs’ limited risk bearing capacity implies that volatility has a direct impact on arbitrage. The existence of conditional volatility in financial time-series is a well established phenomenon. This is tackled in conditional volatility models, often related to Generalised Autoregressive Conditional Heteroskedasticity (GARCH) models (Engle 1982, Bollerslev 1990). But existing literature commonly suffers from employing relatively low frequency data (i.e. monthly or lower) and/or constant variance processes thereby missing this crucial volatility channel and risking variance misspecification.

We develop a framework of market segmentation as a source of swap market frictions, by extending a preferred-habitat model of the fixed income market with arbitrage bounds on swap markets to derive international channels of monetary transmission. We adapt the model to an open economy setting by considering arbitrage along two dimensions: A domestic dimension, driven by term- and credit-structure, and an international dimension, driven by financial intermediation costs on swap markets. Our model closely follows Altavilla et al. (2015) for domestic arbitrage but

\footnote{See Bhattarai and Neely (2018) for a comprehensive review.}
in order to be compatible with an open economy setting, it does not feature any term-structure in arbitrage portfolios. Instead we consider a more general portfolio of assets that arbitrageurs optimise, subject to market and credit risk. The inclusion of cross-currency frictions follows the setting of bounded CIP arbitrage, proposed by Sushko et al. (2017). We employ a measure of policy asymmetry instead of their measure of hedging demand to expose specific policy transmission channels. Monetary policy enters the model by changing rate expectations and local asset supply, which affects arbitrage demand and the market price of risk, and hence pricing through the volatility premium on assets. This corresponds with Gabaix and Maggiori (2015) and Avdjiev et al. (2016) who, among others, highlight the risk-structure as driver to open arbitrage opportunities. Empirically, we employ two policy measures: a daily measure of monetary policy attention, based on Google search data, and a measure of month ahead policy-rate expectations based on futures data, which we use in a set of exponential-GARCH-in-Mean (EGARCH-M) models (Nelson 1991). We find significant GARCH-in-mean effects on the USD/EUR cross-currency basis, providing evidence for the existence of a volatility premium, as well as significant effects of policy asymmetries on swap markets. In our setting, swap market disequilibria are caused by a combination of policy asymmetries and volatility premia, which persisted due to frictions affecting swap market arbitrage. The existence of a volatility premium and its link to policy measures suggests that, following preferred habitat theory, the effect of policy on swap market disequilibrium is endogenously exacerbated through the effect of volatility on swap market frictions. In other words, in addition to direct channels, through its effect on volatility, policy can mitigate or add to frictions and thereby have a narrowing or widening effect on cross-currency bases. We replicate the analysis for several different maturities of the cross-currency basis swap (CCBS) rate, finding strikingly different dynamics on money and capital markets possibly following differences in policy effectiveness across the term structure at the time.

Our research adds to the understanding of policy channels affecting disequilibrium on international financial markets in the light of market frictions arising in the post-crisis period. In particular, we show how, in the presence of market segmentation with arbitrageurs facing credit and market risk, policy affects swap markets directly through asset pricing as well as indirectly through a volatility channel. We further empirically show, how, when considering high frequency data and allowing for conditional volatility, there is a significant impact of the volatility premium on swap market frictions. The impact of the volatility channel is, where significant, relatively large and tends to dominate direct policy effects.

The remainder of this paper is structured as follows: The next section gives a brief outline of the CIP puzzle and evolution of recent European and US monetary policy, section 3 derives our model and highlights particular policy channels in it and section 4 investigates the problem empirically with respect to European and US markets. Section 5 offers and outlook and conclusions.
2 Swap Markets and Monetary Policy Post GFC

2.1 The CIP Condition and the Cross Currency Basis

Covered interest parity implies that return differences for otherwise equal domestic and foreign assets should be explained by (hedged) exchange rate differences, hence

\[ (1 + y_t) = \frac{f_t}{s_t}(1 + y^*_t), \quad (1) \]

where \( y_t \) denotes the yield on a domestic asset at time \( t \), \( y^*_t \) the yield of a foreign asset, \( f_t \) forward, and \( s_t \) spot exchange rates at \( t \). Using a logarithmic approximation, we can re-write (1) in terms of the forward spread as

\[ f_t - s_t = \frac{(1 + y)}{(1 + y^*)} \approx y - y^*. \quad (2) \]

(2) is a no-arbitrage condition as, in the absence of frictions and exchange rate risk, risk-less profits could be realised through cross-currency swaps. The resulting price of such swaps is the cross-currency basis, \( b \), which in the no-arbitrage case can be expressed as

\[ b = y_t - \left( y^*_t + f_t - s_t \right) = 0. \]

Conversely, some non-zero \( b \) can be interpreted as the degree to which the CIP condition is violated. Violations persist and can be caused through frictions to arbitrage on swap markets, such as banks facing wholesale refunding costs on repo markets, market liquidity premiums on swap markets, and costs of banks’ balance sheet exposure arising from counterparty risk on FX swap hedging demand. In our model we assume frictions arising from such hedging demand shocks.

2.2 USD/EUR Cross-Currency Basis, Risk and Monetary Policy

In the aftermath of the great financial crisis foreign exchange markets have been characterised by frequent persistent violations of the covered interest parity condition. Figure 1 gives the evolution of the 3m-5y USD/EUR CCBS and implied volatility of S&P 500 options (VIX) post 2008. Up until the end of 2013 we can see the cross currency bases widening, which coincides with VIX movements around the financial crisis and the Eurozone crisis. [Sushko et al. (2017)] explain these violations with heightened counterparty- and market risk during crisis times. However, from 2014 onwards, the currency basis persistently widened again despite VIX indicating relatively low volatility, suggesting that risk-factors alone are insufficient in explaining the disequilibrium.
Looking at monetary policy conditions at the time adds an interesting perspective. Figure 2 plots policy rate futures for the US (FFUS) and the Eurozone (FFEU), which we use as proxies for rate-setting expectations. Whilst for large parts of crisis periods, both FED and ECB entered an aggressive easing cycle, albeit a short period of (failed) early attempts of monetary contraction in Europe, policy expectations appeared to diverge from 2014 onwards. This is linked to the FED initiating a policy contraction with the tapering of its asset purchase programmes in 2013 and further with first interest rate hikes in 2014, while the ECB eased monetary conditions further at the time, allowing for negative deposit rates and implementing its first large-scale asset purchase programme.

This first evidence suggests that there is a link between policy divergence and the recent failure of the CIP condition.
3 Model

To investigate policy effects on the failure of the covered interest parity condition we derive a structural framework based on two approaches: A model for arbitrage bounds on swap markets, caused by intermediation frictions, and a preferred habitat model of fixed income pricing, based on a mean-variance optimisation of domestic arbitrage portfolios.

Accordingly, we assume an economy with two types of agents, arbitrageurs and investors. Arbitrageurs specialise in (1) CIP arbitrage or (2) fixed income (FI) arbitrage.

3.1 CIP Arbitrage

The cornerstone of CIP arbitrage is the cross-currency basis, $\hat{b}$, which forms a set of arbitrage bounds, $\hat{b}^- \geq \hat{b} \geq \hat{b}^+$, such that²

\[
\hat{b}^- \equiv y_t - (y^*_t + f_t - s_t) \geq -\theta_t \rho \sigma_s^2 D_t^{XC} - c \left( (r_t^{REPO} - r_t) - \left( r_t^{*,REPO} - r_t^* \right) \right) \\
- \left[ (f_t^B - s_t^A) - (f_t^A - s_t^B) \right] / 2
\]

\[
\hat{b}^+ \equiv y_t - (y^*_t + f_t - s_t) \leq \theta_t \rho \sigma_s^2 D_t^{XC} + c \left( (r_t^{REPO} - r_t) - \left( r_t^{*,REPO} - r_t^* \right) \right) \\
+ \left[ (f_t^B - s_t^A) - (f_t^A - s_t^B) \right] / 2,
\]

(3)

²See appendix A.1 for details.
where $y_t$ and $y^*_t$ are domestic and foreign yields, respectively, $f_t$ and $s_t$ are forward and spot exchange rates, $\theta_t$ is a time-varying parameter governing counter-party credit default risk probability on forward swap markets, $p$ gives the coefficient of absolute risk aversion with respect to the exchange rate variance, $\sigma^2_t$, $D_{XC}^t$ gives hedging demand shocks, and $c$ gives a fraction of CIP arbitrage funded via REPO markets, with $r^{REPO}_t$ and $r^{*,REPO}_t$ giving respective domestic and foreign wholesale refunding rates.

The LHS of the inequality in (3) directly follows from the CIP relation. Arbitrage opportunities arise from differences between domestic and (hedged) foreign yields, $y_t$ and $(y^*_t + f_t - s_t)$, respectively. In the presence of interest parity it is zero. The RHS gives persistent CIP deviations, which are a function of balance sheet costs, which in turn are sensitive to aggregate demand shocks, and intermediation/transaction costs. In other words, this reflects imperfect CIP arbitrage.

### 3.2 FI Arbitrage

Yields are priced on a segmented fixed income market, where FI arbitrageurs exploit arbitrage opportunities, arising from the price-inelastic asset demand of preferred habitat investors. Accordingly, yields, $y^*_t$ are priced as

$$y^*_t = \frac{1}{n} \sum_{j=0}^{n} E_t \left( (\bar{b}_t + \gamma) \Sigma \lambda_t + j \right)$$

and

$$y^*_t = \frac{1}{n} \sum_{j=0}^{n} E_t \left( \frac{(\bar{b}_t + \gamma) \Sigma \lambda_t + j}{n} \right)$$

(4)

Describes yield pricing as an expected path of premia over short-term interest rates, $r$. Such premia arise as credit premia, driven by a set of structural macro-factors, $X_t$, and volatility premia, driven by the underlying asset variance, $\Sigma \Sigma'$, the market price of risk, $\lambda$, and bond pricing and credit-risk coefficients, $b_t$.

The dynamics of fixed income arbitrage enter through the market price of risk, $\lambda$, such that

$$\lambda_t = \sigma \sum_{i=1}^{N} (S^i_t - \xi^i_t)(\bar{b}_t + \gamma),$$

(5)

**3** Owing to the high degree of collateralisation, swaps are usually considered default-risk free trades. However, Sushko et al. (2017) highlight that cross-currency basis swaps carry the residual risk of some counterparty being stuck with foreign-currency denominated collateral. Although this default-risk probability is considered small, given the size of the underlying market and hence the associated balance sheet exposure, it can cause considerable frictions.

**4** See appendix A.2 for the corresponding arbitrage portfolio optimisation.
which is a function of risk aversion, \( \sigma \), arbitrage demand, given as difference between local asset supply, \( S^l_t \), preferred habitat demand, \( \xi^l_t \), and the pricing coefficients \( \beta^l \) and \( \gamma^l \).

### 3.3 Monetary Policy Transmission

**Domestic Transmission Channels** Monetary policy enters through its effects on domestic fixed income pricing or through its effects on CIP arbitrage. For the former, it affects domestic yield pricing through either asset supply, \( S^l_t \), affecting arbitrage demand and the market price of risk, or through its impact on the expected path of policy rates, \( \frac{1}{n} \sum_{j=0}^{n} E_t(r_{t+j}) \). In terms of transmission channels, we can think of asset purchases entertaining some broad portfolio-rebalancing channel and rate expectations a forward guidance/signalling channel. Asset purchases further affect risk, and hence a volatility premium on mean asset returns. Policy therefore further affects market returns through a volatility channel.

**Transmission via CIP Arbitrage** CIP arbitrage frictions can arise from three sources: Hedging-demand shocks, swap market liquidity, and wholesale refunding liquidity. The significance of policy on hedging demand is through policy asymmetries affecting relative prices of foreign to domestic assets, inducing portfolio rebalancing behaviour and therefore changes in foreign currency exposure. The change in FX exposure then implies changes to hedging demand. It is important to note that the strength of this effect depends not only on changes in FX exposure but also on changes to any of the risk parameters involved. Swap market liquidity can be estimated as simple bid-ask spread and is affected by both, domestic and foreign market activity as well as policy interventions. Wholesale refunding liquidity captures local wholesale refunding costs on repo markets as premium of repo rates over respective interbank rates. Here, central bank interventions could have asymmetric effects, which could cause spill-overs on FX swap markets. Examples of policy interventions to address liquidity premiums include extended liquidity provisions on local fixed income markets (predominantly used by the ECB) and provision of foreign currency denominated liquidity through swap agreements between 6 major central banks.

**Policy and the Currency Basis** Since policy asymmetries affect relative prices between domestic and foreign assets, following resulting yield spreads transmit onto \( \hat{b} \). Were a binding no-arbitrage condition, the inequalities would disappear and the yield differential would necessarily sum to zero. However, to the extend that frictions on swap markets imply costs to cross-currency arbitrage, \( \hat{b} \) is bounded away from zero and hence \( \hat{b} \) can be non-zero and return differences are tolerated on swap markets. The impact of policy on \( \hat{b} \) stems from the degree to which policy causes rate differences and hence opens arbitrage opportunities on swap markets, which causes shocks to swap demand, \( D^{XC}_t \). This implies that any asymmetries of the factors that affect domestic and foreign yields in lead to a widening of \( \hat{b} \), which the frictions in proposed by (Sushko et al. 2017), prevent from closing. In this

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5Participating central banks were: Federal Reserve, ECB, Bank of England, Bank of Japan, Swiss National Bank, Bank of Canada. There were further bilateral swap agreements between central banks.
setting domestic policy has spillover effects, and hence affects foreign assets. Similarly, policy affects asset volatility for both domestic and foreign assets. There is therefore an impact of policy on FX volatility, $\sigma^2_s$. Furthermore, the CIP arbitrage channel gives policy a direct impact on the cross currency basis through its effects on arbitrage liquidity.

To expose aforementioned transmission channels we first write 4 in terms of premiums over a risk less benchmark, 6

$$y_t = \frac{1}{T} \sum_{i=1}^{T} \text{Er}_{t+i} + CP(x, \epsilon) + VP(\gamma, \lambda(\sigma, \omega, \xi), b, \gamma, \Sigma, \Sigma'),$$

where $CP$ denotes a credit premium, collecting the second term in 4 and $VP$ represents a volatility premium, capturing the remainder of the equation. Substituting for 6 in 3 gives

$$\hat{b} = \left( \frac{1}{T} \sum_{i=1}^{T} \text{Er}_{t+i} - \frac{1}{T} \sum_{i=1}^{T} \text{Er}_{t+i}^* \right) + (CP - CP^*) (VP - VP^*),$$

$$\text{where } \Lambda \text{ denotes swap market arbitrage frictions and collects terms affecting wholesale refunding and swap market liquidity. Accordingly, policy asymmetries feed into 3 directly through causing rate differences as well as indirectly through its effects on CIP arbitrage.}$$

4 Application: Conditional Volatility, Policy, and the EUR/USD Basis

We test for aforementioned policy channels in 3 directly through analysing the effect of asymmetric policy on the EUR/USD cross-currency basis in a GARCH-in-Mean framework.

4.1 Data

We employ a sample of US and European daily fixed income, foreign exchange and Google search data from January 1st 2014 - June 30th 2016. The data is chosen in order to capture policy asymmetries between the ECB and the FED, which were particularly strong at the time.

*For the ease of composition, we omit the respective equation for $y^*$, which is similar.*
Figure 3 plots the evolution for CCBS rates considered. Whilst generally a widening of CCBS is observable for all maturities, money and capital markets appear to follow different patterns, particularly towards the end of the sample. This is particularly striking when considering the 3mth and 5y bases: Initially, 3mth CCBS were widening the most, whilst the 5y CCBS was narrowest. This situation is reversed towards the end of the sample. CCBS rates of different maturities appear generally less cointegrated, which indicates a greater degree of market segmentation.

This situation is exacerbated for forward spreads (Figure 4), where money market arbitrage, as given by the 3m forward spread, follows a linear clearly negative trend (in line with the negative CCBS), whilst for other maturities there is no apparent or possibly a small positive trend. The striking difference in arbitrage behaviour suggests fundamentally different market dynamics at play. This is, to some degree, unsurprising, given the importance for market liquidity and wholesale refunding on money markets on one hand, and dominating pricing dynamics on capital markets on the other.
Figure 4: Forward Spreads

Liquidity spreads (Figure 5) follow similar patterns across maturities for means and variances, with the 5y swap market liquidity being particularly volatile towards the end of the sample. This corresponds with a relatively sharp drop in the 5Y CCBS rate around the same time and is likely outlier driven, which is reflected in our sample restriction outlined in greater detail in section 4.3.2 below.
Several risk measures are plotted in Figure 6. There are several sharp imbalances for counter-party credit risk, CPRISK, in the early half of our sample. CPRISK in this case gives the difference between OIS-Libor and OIS-Eonia spreads, and the spikes reflect spikes in the EONIA-OIS spread at the time, which coincides with decreases in excess liquidity and several ECB policy rate decreases. Drops in CPRISK towards the end of the sample are due to increases in libor, which was likely linked to US policy rate increases at the time. Asymmetry of wholesale refunding liquidity, REPO, is given as the difference between European and US REPO-liquidity. It drops substantially from the second to the fourth quarter of 2015, with spreads briefly turning negative in the last two quarters of 2015. This drop in REPO coincides with further ECB policy rate decreases and the introduction of negative deposit rates in the Euroarea. The yet relatively small reaction in REPO is due to the fact that its US component was sharply increasing at the time, following the underlying change in policy rate regime for the US. In other words, policy asymmetries at the time may have overshadowed the severity of adverse policy effects on European money markets. It is also interesting to note the difference between the two volatility measures considered: Whilst VIX is relatively volatile but appears to revert to a stable mean, FXV shows relatively little fluctuations but seems to have an increasing mean over the sample. The latter follows a similar pattern to that observed for CCBS rates, giving rise to the existence of volatility premia.
Figure 6: Risk Factors

Figure 7 plots the two policy measures employed. Policy asymmetry is measured through rate expectations using policy rate futures, FF, and a measure of monetary policy attention based on Google search data, MPSI, as proposed in Wohlfarth (2018). FF shows a clear positive trend, which reflects the diverging policy rate regimes between Fed and ECB. MPSI is relatively noisy, which is in the nature of the underlying data. However, Wohlfarth (2018) show that the volatility patterns in the underlying policy indices for Fed and ECB coincide with a set of significant policy events at the time. FF is trending positively as a result of the diverging policy environment, which coincides with the negative trends observable in CCBS rates.
4.2 Model Specification

Following eq. 7, we estimate a mean-variance relationship for the currency basis swap rates considered as EGARCH-in-Mean models, such that

$$\hat{b}_t = x'_t \beta + \nu_t \tag{8}$$

where

$$x' = (1 \ \log h_t \ \text{FF}_t \ \text{FWD}_t \ \text{REPO}_t \ \text{Liquidity}_t \ \hat{b}_{t-1})$$

and

$$\nu_t = \varepsilon h_t^{1/2}, \ \varepsilon \sim \text{IID}(0,\Sigma)$$

and

$$\log h_t = c_0 + c_1 h_{t-1} + c_2 \frac{\nu^2_{t-1}}{h_{t-1}} + c_3 \frac{\nu^2_{t-1}}{h_{t-1}} + c_4 \text{VIX} + c_5 \sigma^2_t + c_6 \text{MPSI}_t.$$ 

$\beta$ is a $7 \times 1$ coefficient vector, $\hat{b}_t$ denotes the respective EUR/USD CCBS rate, $\text{FF}$ gives the difference between front-month policy rate futures for the US and the Eurozone, $\text{FWD}$ is the forward spread, given as difference between spot and respective forward exchange rates, and $\text{MPSI}$ the difference in policy attention indices based on Google search data. We further control for the wholesale refunding liquidity premiums, captured through the LIBOR-REPO spread, $\text{REPO}$, a swap market liquidity premium, $\text{LIQUIDITY}$, given by bid-ask spreads on FX spot.
and forward markets, and a counter-party risk premium, \( \theta \), captured through OIS-LIBOR spreads. \( VIX \) gives implied volatility of S&P 500 options as a general proxy for market risk and \( \sigma_s^2 \) is implied volatility on USD/EUR foreign exchange options as a proxy for FX market risk.  

4.3 Results

Results for the models specified in \( \text{Eq. 3.1} \) are given in table 1 below. We further consider a restricted sample in table 2, covering data from January 2014-November 2015, owing to the presence of outliers in the full sample.  

4.3.1 Full Sample

Policy asymmetry as measured by futures enters significantly across the whole term structure of CCBS. It is only insignificant for the 1y pocket, which is almost entirely driven by the forward spread. It is negative on capital markets (2Y and 5Y), hence widening the (negative) currency basis, whilst we find the opposite effect on money markets (3m). We find significant negative GARCH-in-Mean effects for 2Y and 5Y CCBS. For the former, the coefficient size is similar to \( FF \), whilst for the latter GARCH-in-Mean effects clearly dominate. Policy attention, \( MPSI \), enters the variance significantly for 5Y and 3m CCBS. In the case of the 5y CCBS, as it further affects means through GARCH-in-Mean, there is evidence for policy transmission via the aforementioned volatility channel. The fact that this evidence appears for longer CCBS maturities may be due to MPSI capturing more unconventional policies, such as quantitative easing measures, which were dominant on capital markets. MPSI enters negatively on capital markets, suggesting a mitigating effect of policy on uncertainty, and positively on money markets. We hence observe similarly different dynamics for money and capital markets than we have for the direct effect of rate expectations in means.

Generally, 3mth CCBS appears to be almost entirely driven by market liquidity. This is indicating money market dynamics, which are typically sensitive to traded flow volumes. Given the close link to wholesale refunding on money markets, it is somewhat surprising to not find significant effects of REPO liquidity on the short end of the currency basis. This is, however, in line with the shift to unsecured money market funding operations, documented in Rime et al. (2016). This shift away from wholesale refunding operations could further indicate adverse effects of policy measures on money markets at the time. Beaupain and Durré (2016) provide evidence for adverse effects of ECB’s fixed rate full allotment (FRFA) policy introduced in October 2008. Accordingly, following the introduction FRFA, money market liquidity was positively affected by excess reserves, held at central bank deposits. Policy

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7The models assume stationarity and a variables are differenced accordingly. Specification tests, addressing structural stability and potential endogeneity problems are given in appendix B.

8In particular, there is evidence of an outlier on 04/12/2015, which follows a surprise decision of the ECB on 03/12/2015 to extend its EAPP by less than expected as well early misreporting of the policy decision by the financial time. Both is likely to have contributed to abnormally high volatility on markets.

9As we discuss further in appendix B.2, results for 1Y CCBS rates should be treated with a degree of caution due to the presence of several endogeneity problems. Given the small explanatory power of the model for both, the full and restricted sample, we do not investigate the issue further.
efforts to reduce excess reserves, such as the introduction of negative deposit rates, may have further exacerbated this situation on Repo markets causing arbitrageurs to shift away from wholesale refunding activities. The positive coefficient of FF supports this: It could be indicative of asymmetry having offset some of the adverse policy effect on market liquidity and therefore contributed to some narrowing of the basis. In other words: to the degree that domestically successful policies helped closing the cross-currency basis on capital markets (and hence international policy asymmetries contributing to it widening again), domestically unsuccessful policies had a widening impact on the cross currency basis, therefore international asymmetries offset some of this adverse effect. Risk factors enter the variance positively for capital markets, with the effect being dominated by counter-party risk, CPRISK. There is a small, significantly negative effect of VIX on 3mth CCBS. There are significant negative effects of changes in the forward spread and REPO liquidity on capital markets, which is in line with Sushko et al. (2017). On money market CCBS, the forward spread has a small, significantly positive effect on 3m CCBS. FX swap market liquidity is significant in almost all models, with signs switching between maturities, which might indicate local supply scarcity alongside portfolio-rebalancing effects. Coefficient sizes are large and the effect increases dramatically towards longer maturities.

Table 1: CCBS Regressions Full Sample

<table>
<thead>
<tr>
<th>Mean</th>
<th>3m</th>
<th>1y</th>
<th>2y</th>
<th>5y</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOG(GARCH)</td>
<td>-0.076659</td>
<td>-0.037697</td>
<td>-0.096074 *</td>
<td>-0.142886 *</td>
</tr>
<tr>
<td>C</td>
<td>-0.042076</td>
<td>-0.012909</td>
<td>-0.055367</td>
<td>-0.050391</td>
</tr>
<tr>
<td>D(FF)</td>
<td>0.046762 *</td>
<td>-0.039976</td>
<td>-0.098557 ***</td>
<td>-0.054404 **</td>
</tr>
<tr>
<td>D(S-FWD)</td>
<td>0.001871 ***</td>
<td>-7.947805 ***</td>
<td>-4.481749 ***</td>
<td>-1.443949 ***</td>
</tr>
<tr>
<td>D(REPO)</td>
<td>-0.001302</td>
<td>0.002492</td>
<td>-4.921482 ***</td>
<td>-4.079129 ***</td>
</tr>
<tr>
<td>D(LIQUIDITY)</td>
<td>0.001041 ***</td>
<td>3.552487</td>
<td>-5.78537 *</td>
<td>105.9173 ***</td>
</tr>
<tr>
<td>D(CIP(-1))</td>
<td>5.37E-02 **</td>
<td>-0.057396 *</td>
<td>0.056469 **</td>
<td>0.03874</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Variance</th>
<th>3m</th>
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<th>5y</th>
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</thead>
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<tr>
<td>C(8)</td>
<td>-0.328143 ***</td>
<td>-0.063206</td>
<td>-0.306298 ***</td>
<td>-0.232261 ***</td>
</tr>
<tr>
<td>ARCH</td>
<td>0.161073 ***</td>
<td>0.401889 ***</td>
<td>0.021723</td>
<td>0.045919</td>
</tr>
<tr>
<td>Leverage</td>
<td>-0.028319</td>
<td>0.036822</td>
<td>0.274232</td>
<td>0.270542 ***</td>
</tr>
<tr>
<td>GARCH</td>
<td>0.031949</td>
<td>-0.707102 ***</td>
<td>0.546709 ***</td>
<td>0.368307 ***</td>
</tr>
<tr>
<td>D(VIX)</td>
<td>-0.079122 **</td>
<td>0.06896</td>
<td>0.105824 ***</td>
<td>0.066327 *</td>
</tr>
<tr>
<td>D(FXV)</td>
<td>-0.120332</td>
<td>0.090773</td>
<td>0.45344 ***</td>
<td>0.313746 ***</td>
</tr>
<tr>
<td>D(CPRISK)</td>
<td>2.462888</td>
<td>1.839951</td>
<td>12.48306 ***</td>
<td>14.20432 ***</td>
</tr>
<tr>
<td>D(MPSI)</td>
<td>0.045344 ***</td>
<td>-0.006184</td>
<td>-0.001212</td>
<td>-0.021166 *</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>t-DoF</th>
<th>3</th>
<th>3</th>
<th>3</th>
<th>3</th>
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<tbody>
<tr>
<td>R2</td>
<td>0.017722</td>
<td>0.016557</td>
<td>0.08045</td>
<td>0.06975</td>
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<tr>
<td>SER</td>
<td>1.206546</td>
<td>1.290305</td>
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<tr>
<td>BIC</td>
<td>2.649932</td>
<td>2.8722</td>
<td>2.098337</td>
<td>2.385002</td>
</tr>
<tr>
<td>DW</td>
<td>2.001571</td>
<td>2.213993</td>
<td>1.939774</td>
<td>2.008085</td>
</tr>
</tbody>
</table>

The table gives estimation output following the specification in for the full sample (n=881). Dependent variables are 3m-5y CCBS rates. Estimation of all models via maximum likelihood assuming t-distributed errors fixed at 3 degrees of freedom and optimisation using the Eviews legacy algorithm with Marquard steps. BIC gives the Schwarz-Bayes Information Criterion, DW the Durbon-Watson Statistic and SER the standard error of the regression; Significance levels: * < 10%, ** < 5%, *** < 1%.
4.3.2 Restricted Sample

As discussed above, results obtained above may be biased due to the presence of outliers in the sample. We therefore re-estimate the models with a restricted sample, excluding observations from November 2015 onwards, from when we observe several outliers, surrounded by abnormal volatility clusters.

Applying this sample restriction confirms and further strengthens previous results: Most notably, there is a larger effect of the volatility premium as captured through GARCH-M coefficients. This is especially pronounced for the 3mth basis, where it turned from insignificance to being the single largest factor, contributing to a widening of the cross currency basis. This further supports the argument in [Beaupain and Durré (2016)], highlighting the impact of volatility on money markets following ECB’s fixed-rate full allotment policy. However, policy attention is now insignificant. Risk is mostly picked up by \( \text{FXV} \) on capital markets and by \( \text{CPRISK} \) for 1yr CCBS; It is insignificant in 3mth CCBS. In terms of mean effects, we most notably do not observe the strong sign switches of \( \text{Liquidity} \), but instead observe different signs between money and capital markets, which is in line with the other coefficients. We find a large increase in the explained variation of the restricted sample on money markets, whilst the explained variation for the 5Y basis remained fairly unchanged. This suggests the outlier bias to be particularly strong on money markets.
### Table 2: CCBS Regressions Restricted Sample

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>3m</th>
<th>1y</th>
<th>2y</th>
<th>5y</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOG(GARCH)</td>
<td>-6.751313 ***</td>
<td>-0.205103 *</td>
<td>-0.133536 *</td>
<td>-0.184165 *</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-1.691943 ***</td>
<td>-0.03085</td>
<td>-0.097049</td>
<td>-0.104055</td>
<td></td>
</tr>
<tr>
<td>D(100*FF)</td>
<td>0.079349 ***</td>
<td>0.012152</td>
<td>-0.084388 ***</td>
<td>-0.108059 ***</td>
<td></td>
</tr>
<tr>
<td>D(100*(S-FWD))</td>
<td>0.006514 ***</td>
<td>-10.42602 ***</td>
<td>-4.38857 ***</td>
<td>-1.266779 ***</td>
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<tr>
<td>D(100*REPO)</td>
<td>-0.004473</td>
<td>-0.022921</td>
<td>-0.083572 ***</td>
<td>0.641667</td>
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<tr>
<td>D(100*LIQUIDITY)</td>
<td>2.727021</td>
<td>3.564468</td>
<td>-0.716119 *</td>
<td>-0.075762 ***</td>
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</tr>
<tr>
<td>D(CIP(-1))</td>
<td>6.83E-01 ***</td>
<td>-0.05949</td>
<td>0.067992 **</td>
<td>0.042376</td>
<td></td>
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</table>

#### Variance

<table>
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<tr>
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<th>1y</th>
<th>2y</th>
<th>5y</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(8)</td>
<td>-0.233454 ***</td>
<td>-0.275749 ***</td>
<td>-0.332894 ***</td>
<td>-0.462521 ***</td>
<td></td>
</tr>
<tr>
<td>ARCH</td>
<td>-0.063185</td>
<td>0.395303 ***</td>
<td>-0.092096</td>
<td>0.232781 ***</td>
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</tr>
<tr>
<td>Leverage</td>
<td>0.09915 ***</td>
<td>0.113707</td>
<td>0.236522 ***</td>
<td>0.253678 ***</td>
<td></td>
</tr>
<tr>
<td>GARCH</td>
<td>0.062733 *</td>
<td>-0.066185</td>
<td>0.47601 ***</td>
<td>0.359474 **</td>
<td></td>
</tr>
<tr>
<td>D(VIX)</td>
<td>-0.002155</td>
<td>0.077177</td>
<td>0.051916</td>
<td>0.03304</td>
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<tr>
<td>D(FXV)</td>
<td>0.002002</td>
<td>-0.03333</td>
<td>0.272176 **</td>
<td>0.227262</td>
<td></td>
</tr>
<tr>
<td>D(CPRISK)</td>
<td>0.376049</td>
<td>17.60131 **</td>
<td>-4.414423</td>
<td>-3.321706</td>
<td></td>
</tr>
<tr>
<td>D(MPSI)</td>
<td>0.00103</td>
<td>-2.32E-05</td>
<td>0.005868</td>
<td>-0.005688</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
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<tr>
<td>t-DoF</td>
<td>3</td>
<td>3</td>
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</tr>
<tr>
<td>R2</td>
<td>0.183513</td>
<td>0.034669</td>
<td>0.081347</td>
<td>0.063495</td>
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<tr>
<td>SER</td>
<td>0.894602</td>
<td>0.972518</td>
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<tr>
<td>BIC</td>
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<td>2.67076</td>
<td>2.012825</td>
<td>2.202965</td>
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</tr>
<tr>
<td>DW</td>
<td>2.125185</td>
<td>2.246725</td>
<td>2.037693</td>
<td>1.952789</td>
<td></td>
</tr>
</tbody>
</table>

The table gives estimation output following the specification in (8) for the restricted sample (n=668). Dependent variables are 3m-5y CCBS rates. Estimation of all models via maximum likelihood assuming t-distributed errors fixed at 3 degrees of freedom and optimisation using the Eviews legacy algorithm with Marquard steps. BIC gives the Schwarz-Bayes Information Criterion, DW the Durbon-Watson Statistic and SER the standard error of the regression. Significance levels: * < 10%, ** < 5%, *** < 1%.

### 5 Outlook and Conclusions

We propose a theoretical framework, combining a preferred habitat model of domestic fixed income pricing with a model of FX swap market frictions. This framework shows how policy asymmetries can lead to failure of the CIP condition in the presence of arbitrage frictions. In particular, preferred habitat theory allowing for some credit counter-party default risk probability endogenously exacerbates such a disequilibrium situation. Deviations from CIP are then caused by a combination of policy asymmetries and volatility, which can persist owing to frictions affecting swap market intermediation, such as reported in Sushko et al. (2017) and Du et al. (2017) among others.

We test our theoretical findings empirically in a set of EGARCH-in-Mean models of several market structural factors and policy asymmetries on 3m-5y CCBS rates. We find that both policy and volatility has significantly contributed to the failure of CIP. Swap market volatility is mainly driven by risk, both counter-party and market risk. We also find significant effects of monetary policy attention on CCBS volatility coinciding with significant GARCH-in-Mean effects, which supports the presence of a volatility channel of international policy transmission. There is furthermore evidence
for distinctive dynamics on money markets, suggesting some possible degree of policy ineffectiveness, leading money market dynamics being mainly driven by volatility premia.

Our results show that, when explicitly accounting for conditional volatility, swap market disequilibria are significantly affected by a combination of policy and volatility. The impact of such risk channels is underestimated in models failing to explicitly model conditional variance processes. The effect appears to be particularly severe on money markets, following adverse policy effects. This has important policy implications, highlighting the impact of uncertainty on market returns in general. In our setting policy can affect uncertainty and improve market efficiency, by reducing arbitrage frictions. On foreign exchange markets this effect is exacerbated as volatility, and therefore uncertainty, enters through both, market returns and its effect on swap market efficiency. This emphasises the need to consider the combination of policy-, risk-, and market-structural factors for the analysis of FX imbalances.

These findings open several routes for further research. One feature of our analysis is the direct use of futures as policy measures to capture level effects of policy on returns. But policy-rate futures are affected by the zero lower bound, such as with European futures in our case. To mitigate this, policy measures could be extended following the shadow-rate model, proposed in Wu and Xia (2016) and Wu and Xia (2017), for daily frequencies. Since shadow policy rates have been below policy rates during times when the zero lower bound was binding, using this approach would likely further strengthen the effect of policy asymmetries. There also appear to be changes in the term structure of CCBS rates, that may be affected by some of the variables considered. In particular, analysing the impact of volatility on the term structure might provide further evidence for the preferred habitat effects in our model. Here, estimating a term structure model allowing for time-varying coefficients would be promising. Lastly, whilst our theoretical structure is sufficient to highlight the transmission channels discussed, it could be extended to a general equilibrium framework, allowing for an analysis of international policy transmission on main macroeconomic aggregates and a discussion of implied welfare effects.

References


Coffey, N., Hrung, W. B., and Sarkar, A. Capital constraints, counterparty risk, and deviations from covered interest rate parity. 2009.


A Proofs

A.1 CIP Arbitrage Bounds

Following Sushko et al. (2017), we assume foreign exchange swap markets, where arbitrageurs face the following end-period wealth constraints

\[ E_t[W_{t+1}] = W_t + (W_t - x_{t,f})y_t + [1 - \theta_t]x_{t,f}(f_t^B + y_t^* - s_t^A) + \theta_t x_{t,f}(E_t[s_{t+1}^B] + y_t^* - s_t^A), \]

if \( f_t - s_t > y_t - y_t^* \) and

\[ E_t[W_{t+1}^*] = W_t^* + (W_t^* - x_{t,f})y_t^* + [1 - \theta_t]x_{t,f}(f_t^A + y_t - s_t^B) + \theta_t x_{t,f}(E_t[s_{t+1}^A] + y_t - s_t^B), \]

if \( f_t - s_t < y_t - y_t^* \). (9)

(10)

\( W_t \) denotes the arbitrageurs wealth at time \( t \), \( y_t \) the interest rate of underlying assets in the arbitrage portfolio, \( x_{t,f} \) are the US$ amount of FX swaps, \( f_t^B \) and \( f_t^A \) are forward bid and ask exchange rates and \( s_t^B \) and \( s_t^A \) respective spot rates. \( \theta_t \) is a probability capturing counterparty default risk, which is arising from collateral for swapped cash-flows being denominated in foreign currencies. CIP requires the forward spread to equal rate differences, in which case there would be complete arbitrage on swap markets. The cases given in 9 and 10 are therefore bounds following from the failure of CIP. In 9, a domestic CIP arbitrageur generates wealth in \( t+1 \) through interest earned on domestic assets, (hedged) interest earned on foreign assets (denoted *) or arbitrage profits, arising from exploiting differences between forward rates at \( t \) and expected spot rates at \( t+1 \). A foreign CIP arbitrageur takes the counterparty position on swap markets, switching bid and ask rates on swap markets as well as domestic and foreign interest rates. The inequalities between the forward spread and rate differences in 9 and 10 arise from the collateral exposed to counterparty risk, when \( \theta > 0 \).

Assuming an exponential utility function, \( -E_t[(-rW_{t+1})] \), gives the following certainty-equivalent objective function for 9

\[ \max_{x_{t,f}} \{ W_t(1 + y_t) + x_{t,f}(f_t^B - S_t^A + y_t^* - r_t) - \frac{\rho}{2} \theta_t x_{t,f}^2 \sigma_s^2 \} \]  \hspace{1cm} (11)

which, imposing market clearing, \( x_{t,f} = D_t^{NC} - \Lambda \), gives the forward rate as 10

\[ f_t^B = s_t^A + y_t - y_t^* + \theta_t \rho \sigma^2 D_t^{NC} - \Lambda, \] \hspace{1cm} (12)

We apply the same logarithmic approximation as Sushko et al. (2017), i.e. \( F/S - (1 + r)/(1 + r^*) \approx f - s - r + r^* \), where \( f \equiv \log(F) \) and \( s \equiv \log(S) \).
where \(D^{XC}_t\) captures shocks to swap demand, where \(D^{*}_{t, XC} \equiv -D^{XC}_t\), and \(\Lambda\) captures frictions arising from liquidity and transaction costs.\(^{[1]}\)

From the CIP relationship, a negative cross-currency basis follows

\[
\hat{b}^-_t \equiv y_t - (y^*_t + f_t - s_t) \\
\geq \theta_t \rho \sigma^2 D^{XC}_t - \Lambda
\]

(13)

and equivalently

\[
\hat{b}^+_t \equiv y_t - (y^*_t + f_t - s_t) \\
\leq \theta_t \rho \sigma^2 D^{XC}_t = \Lambda,
\]

(14)

which are the arbitrage bounds, given in section 3.1. □.

### A.2 FI Arbitrage Portfolio Optimisation

Assume an economy with two types of agents – arbitrageurs and investors. Arbitrage arises as holding return \(R^P_{(t,t+1)}\) of a security between two respective periods. Eq. \([15]\) describes arbitrageurs’ preferences based on a mean-variance objective function:

\[
E_t R^P_{(t,t+1)} - \frac{1}{2} \sigma \text{Var}_t R^P_{(t,t+1)}
\]

(15)

\[
R^P_{(t,t+1)} = \sum_{i=1}^N \omega^i_t R^i_{(t,t+1)} = \sum_{i=1}^N \omega^i_t \left[ \exp(\overline{p}^{i}_t) - 1 \right]
\]

where \(\omega^i_t\) represents the share arbitrageurs’ holdings of bonds in habitat \(i\) relative to their net wealth \(W_t\), and \(\overline{p}^{i}_t\) is the price of a bond in habitat \(i\) at time \(t\). These bonds are subject to credit risk, measured as risk intensity parameter \(\psi_t\), such that

\[
\overline{p}^{(0)}_{t+1} = \begin{cases} 1, & \text{with probability } \exp(-\psi_{t+1}) \\ 0, & \text{with probability } 1 - \exp(-\psi_{t+1}) \end{cases}
\]

which is affine in a set of macroeconomic factors

\[
\psi_{t+1} = \gamma' X_{t+1}
\]

(16)

which follow the VAR process

\[
X_t = \mu + \Phi X_{t-1} + \varepsilon_t \quad \varepsilon_t \sim N(0, \Sigma')
\]

(17)

with log-bond prices of a pure-discount habitat \(i\), default-risk-less bond given as

\[
\overline{p}^i_t = -\pi^i_t - \hat{b}^i_t X_t,
\]

\[^{11}\Lambda_t = c(\overline{y}^{REPO}_t - y^*_t) - (\overline{y}^{REPO}_t - y^*_t) + [(f^A - s^A_t) - (f^A - s^B)]\), which gives frictions arising from wholesale funding costs (where \(y^{REPO}_t\) gives repo rates) and liquidity costs arising from bid-ask spreads. Both are assumed constant and exogenous in the following, giving the expression in \([11]\).\]
its corresponding risk-free one-period rate as
\[ y_i^t = a_i + b_i' X_t, \]
and the continuously compounded yield \( y_i^t \) on a \( n \)-period bond in habitat \( i \) as \( -p_i^n/n \). Arbitrageurs’ portfolio holding return can be expressed as
\[
R_P(t, t+1) = N \sum_{i=1}^{N} \omega_i^t \left[ \exp\left( -a_i - b_i' X_{t+1} + a_i + b_i' X_t \right) - 1 \right]
\]
where an arbitrageur chooses \( \omega_i^t \) such that \[ \max E_t[R_P^P(t, t+1)] - \frac{1}{2} \sigma Var_t[R_P^P(t, t+1)] \]
s.t. : \[ \sum_{i=1}^{N} \omega_i^t = 1 \]
and for small time increments we can approximate the conditional variance, \( \text{Var}_t[R_P^P(t, t+1)] \), and the conditional expected mean return, \( E_t[R_P^P(t, t+1)] \), such that \[ E_t[R_P^P(t, t+1)] \approx \sum_{i=1}^{N} \omega_i^t \left[ (-\bar{b}_i + \gamma)(\mu + \Phi X_t) \right. \]
\[ + \frac{1}{2}(\bar{b}_i + \gamma)\Sigma \Sigma' (\bar{b}_i + \gamma) + \bar{b}_i X_t) \right] \]
\[ \text{Var}_t[R_P^P(t, t+1)] \approx \omega_i^t \Sigma \Sigma' \omega_i^t, \]
12 The mean-variance objective function in (20) can be seen as no-arbitrage condition, where any positive difference, must be the result of an arbitrage opportunity, realised through the choice of \( \omega_i^t \).

13 Hamilton and Wu (2012) show that for \( q_{n,t+1} \equiv \frac{P_{(t,t+1)} - P_{(t,t)}}{P_{(t,t)}} = \exp \left( \mu t + \sqrt{t} \epsilon_{t, t+1} \right) - 1, \ (\epsilon_{1,t+1}, \ldots, \epsilon_{N,t+1})' \sim N(0, \Omega) \), the continuous time representation of a discrete time process,
\[
E_t \left( \sum_{i=1}^{N} z_it R_{P_{(t,t+1)}} \right) = \sum_{i=1}^{N} z_i t \left[ \mu + \Omega_{ii} h/2 + o(h) \right]
\]
\[ \text{Var}_t \left( \sum_{i=1}^{N} z_it \right) = z_i' \Omega z_i h + o(h), \]
for \( h = 1 \) and \( o(h) = 0 \) leads to
\[ \frac{P_{(t,t+1)}}{P_{(t,t)}} = \exp[\bar{b}_i (X_{t+1} - X_t)] \]
\[ \mu_n = \bar{b}_i (\epsilon + \gamma X_t) - \bar{b}_i X_t \]
\[ \Omega_{ii} = \bar{b}_i' \Sigma \Sigma' \bar{b}_i, \]
which implies (21).
where
\[ d = \sum_{i=1}^{N} (\omega_i^t (b_i + \gamma)) \]
represents a factor of exposure to macroeconomic risk.

The FOCs of the Lagrangean, \( L_t \), corresponding with (21) are
\[
\frac{\partial L_t}{\partial \omega_i^t} = -(\tilde{b}_i^t + \gamma^t)(\mu + \Phi X_t) + \frac{1}{2}(\tilde{b}_i^t + \gamma^t)\Sigma\Sigma' (\tilde{b}_i^t + \gamma^t) + \tilde{b}_i^t X_t \]
(22)
\[ - (\tilde{b}_i^t + \gamma^t)\Sigma\Sigma' \sigma \sum_{i=1}^{N} [\omega_i^t (b_i + \gamma)] - \chi_t = 0, \]
where \( \chi_t \) is the Lagrange multiplier of the constraints.

Expressing the FOCs in terms of excess holding returns then yields
\[
R_i^{t,t+1} - \tau_t = \tilde{b}_i^t \Sigma \Sigma' \lambda_t
\]
(23)
Investors follow their preferred-habitat motifs over specific maturities in their demand as
\[ \xi_i^t = \varphi (\tilde{y}_i^t - \beta^i) \]
(24)
where \( \xi_i^t \) is the demand relative to the arbitrageurs’ net wealth \( W_t \), and \( \beta^i \) its intercept. In equilibrium the combined demand from arbitrageurs and investors then needs to equal the supply of bonds \( S_i^t \)
\[ \omega_i^t + \xi_i^t = S_i^t \]
(25)
which combined with (23) gives the market price of risk as
\[ \lambda_t = \sigma \sum_{i=1}^{N} (S_i^t - \xi_i^t) (b_i + \gamma) \]
(26)
Using (24) in (26) and rearranging the FOCs in terms of bond yields, \( \tilde{y}_i^t \), gives
\[ \quad \square \]
A.3 Proof of Eq. (7)

Substituting 6 into 7 and assuming swap market equilibrium we get

\[ \hat{b} \equiv \left[ \frac{1}{T} \sum_{i=1}^{T} E r_{t+i} + CP(x, i) \times VP(\gamma, \lambda(S, \xi, \bar{b}, \gamma), \Sigma \Sigma') \right] - \left( \frac{1}{T} \sum_{i=1}^{T} E r_{t+i}^* + CP(x, i)^* \times VP(\gamma, \lambda(S, \xi, \bar{b}, \gamma), \Sigma \Sigma')^* \right) + f_t - s_t \]

\[ + \theta \rho \sigma^2 (\sigma^2, \sigma^2)^* D_t^{XC}(y, y^*) + \Lambda(r, r^*, r_{REPO}, r_{REPO}^*, f_A, f_B). \]

(27)

Rearranging gives 7. □
B Specification Tests

This section discusses problems arising from structural instability of the series and endogeneity of the covariates.

B.1 Structural Stability

The presence of structural breaks in the data would bias the estimates. We therefore test for the presence of unspecified breaks using a Quandt-Andrews breakpoint test. To proceed with the test, we employ the full mean specification as given in 8 and test for unknown breaks in all parameters, choosing standard interval sizes. We execute the tests for all models and compare results for restricted and unrestricted samples. Results are given in table 13 below.

Table 3: Quand-Andrews Breakpoint Tests

<table>
<thead>
<tr>
<th>Statistic</th>
<th>3M</th>
<th>1Y</th>
<th>2Y</th>
<th>5Y</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full</td>
<td>Restr.</td>
<td>Full</td>
<td>Restr.</td>
</tr>
<tr>
<td>Maximum LR F-statistic</td>
<td>0.0171</td>
<td>0.0009</td>
<td>0.0084</td>
<td>0.0257</td>
</tr>
<tr>
<td>Maximum Wald F-statistic</td>
<td>0.0171</td>
<td>0.0009</td>
<td>0.0084</td>
<td>0.0257</td>
</tr>
<tr>
<td>Exp LR F-statistic</td>
<td>0.4499</td>
<td>0.0043</td>
<td>0.2256</td>
<td>0.0883</td>
</tr>
<tr>
<td>Exp Wald F-statistic</td>
<td>0.0882</td>
<td>0.0003</td>
<td>0.0175</td>
<td>0.0272</td>
</tr>
<tr>
<td>Ave LR F-statistic</td>
<td>0.3183</td>
<td>0.0007</td>
<td>0.1356</td>
<td>0.0239</td>
</tr>
<tr>
<td>Ave Wald F-statistic</td>
<td>0.3183</td>
<td>0.0007</td>
<td>0.1356</td>
<td>0.0239</td>
</tr>
</tbody>
</table>

Based on maximum test statistics, the null of no breaks is rejected for all models with break dates corresponding around late November-early December for all models. Expected and average test statistics are more ambiguous for models of the 3m and the 1y basis. The dates suggested fall within the area of sample restriction, for which we have previously detected outliers. We also detect evidence for the presence of breaks in the restricted sample. However, the breaks do neither correspond with particular dates across models nor with outliers detected in residual. Conducting a series of Bai-Perron multiple breakpoint tests, largely confirms the assumption of only one break in December 2015. Results of Bai-Perron tests are given in table 14 below. Given the aforementioned results, we proceed with the assumption of structural stability with respect to the restricted sample.

Table 4: Bai-Perron Tests

<table>
<thead>
<tr>
<th>Bai-Perron</th>
<th>3m</th>
<th>1y</th>
<th>2y</th>
<th>5y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scaled F-statistic (1 vs. 2 breaks)</td>
<td>24.21997</td>
<td>10.0691</td>
<td>16.05189</td>
<td>15.46783</td>
</tr>
<tr>
<td>1st break</td>
<td>12/04/2015</td>
<td>1/21/2016</td>
<td>12/04/2015</td>
<td>10/16/2015</td>
</tr>
<tr>
<td>2nd break</td>
<td>11/04/2014</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

14For the 3m-basis the Bai-perron test suggests two breakpoints. However, the suggested second breakpoint does not correspond with the breakpoint suggested in Quandt-Andrews tests for the restricted sample and we hence proceed with the assumption of only one break.
B.2 Endogeneity

Covariates in our models may be suffering from endogeneity problems. Whilst this can be due to several causes, we judge that these would most likely be due to simultaneity. We therefore investigate Granger-Causality for each respective cross-currency basis with respect to all covariates, based on a stationary reduced form VAR. Results are given in tables 15 and 16 below.

Table 5: Granger Causality Tests: Full Sample

<table>
<thead>
<tr>
<th>Dependent Variables</th>
<th>DCIP3m</th>
<th>DCIP1Y</th>
<th>DCIP2Y</th>
<th>DCIP5Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(100*FF)</td>
<td>0.4443</td>
<td>0.0318</td>
<td>0.3096</td>
<td>0.6038</td>
</tr>
<tr>
<td>D(100*(S-FWD))</td>
<td>0.6326</td>
<td>0</td>
<td>0.0291</td>
<td>0.1705</td>
</tr>
<tr>
<td>D(100*REPO)</td>
<td>0.256</td>
<td>0.5359</td>
<td>0.7723</td>
<td>0.7123</td>
</tr>
<tr>
<td>D(100*LIQUIDITY)</td>
<td>0.629</td>
<td>0.088</td>
<td>0.5877</td>
<td>0.0283</td>
</tr>
</tbody>
</table>

Based on the full sample, there is evidence of reverse causality for several covariates, in that they are Granger-caused by the respective dependent variables. These endogeneity problems are likely caused by the presence of outliers in the full sample. We therefore repeat the tests for the restricted sample.

Table 6: Granger Causality Tests: Restricted Sample

<table>
<thead>
<tr>
<th>Dependent Variables</th>
<th>DCIP3m</th>
<th>DCIP1Y</th>
<th>DCIP2Y</th>
<th>DCIP5Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(100*FF)</td>
<td>0.7486</td>
<td>0.0623</td>
<td>0.6771</td>
<td>0.7425</td>
</tr>
<tr>
<td>D(100*(S-FWD))</td>
<td>0.1557</td>
<td>0</td>
<td>0.284</td>
<td>0.2532</td>
</tr>
<tr>
<td>D(100*REPO)</td>
<td>0.8589</td>
<td>0.3029</td>
<td>0.8124</td>
<td>0.4057</td>
</tr>
<tr>
<td>D(100*LIQUIDITY)</td>
<td>0.4813</td>
<td>0.9224</td>
<td>0.9714</td>
<td>0.6428</td>
</tr>
</tbody>
</table>

For the restricted sample, most endogeneity problems through reversed causality disappear. For the one year basis, however, the futures- and the forward spreads remain endogenous, where estimates are significant for forward spreads only. This is likely due to the particular dynamics of this market segment, as discussed in section 4.3.1 above. Since there are no further endogeneity problems, we abstain from applying an instrument in this case and refer to results for the 3m and 2y basis instead.