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Preferred Habitat, Policy, and the CIP Puzzle

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Preferred Habitat, Policy, and the CIP Puzzle

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Abstract

A crucial no-arbitrage condition on foreign exchange markets, covered interest parity (CIP), held almost exaclty before the Global Financial Crisis (GFC) and failed since then. CIP deviations have been particularly puzzling in relatively calm markets after 2014. This paper explains deviations from CIP, measured by the cross-currency basis from swaps (CCBS), in terms of significant policy and volatility effects in a preferred habitat model of the Eurodollar swap market. Estimation is done using EGARCH in mean for a set of CCBS maturities. The term structure of the CCBS is further analysied in a Vector Error Correction Model (VECM).

JEL Classifications: E43, E44, E5, F31, G12, G15

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1 Introduction

The foreign-exchange swap market is one of the largest markets in the world, both in size and liquidity. And it fails. Since 2008, its crucial no-arbitrage condition, the covered interest parity (CIP) condition, does not hold. CIP requires that on foreign exchange markets interest rate differentials equal the forward premium between spot and forward exchange rates, closing otherwise existing arbitrage opportunities. CIP held almost exactly before 2008, when substantial cross-currency bases (CCBS), a measure for CIP deviations, emerged. Unlike previous episodes, which only lasted for minutes, or could be explained through small transaction costs, CIP deviations were large and persistent. This reflected a shortage of dollar liquidity, following a sharp decline in collateralised lending on inter-bank markets. Until 2014 a common explanation for this was hence the emergence of risk following the preceding financial crisis: Previous trading models, where derivatives, such as cross-currency swaps, could be marketed to market without considering counter-party risk, such as the "flow-monster"[1], had to be revisited. CIP recovered and currency bases narrowed again, following large liquidity injections by a number of central banks and reforms to money market funds that alleviated some risk. But since 2014 the *CIP Puzzle* returned as parity failed again in relatively calm markets. Despite several important contributions to solving this conundrum, recent CIP failure could not be explained entirely. Another important development that had a large impact on global financial markets at the same time arose from policy: After major central banks' reaction to the global financial crisis (GFC), using unprecedented monetary expansions, the US Federal Reserve (FED) initiated a process of policy normalisation, leading to severe global policy imbalances. This paper proposes a link between such policy asymmetries and dislocations to foreign currency arbitrage, that are at the core of the CIP Puzzle.

We develop a framework of market segmentation as a source of swap market frictions, by combining a preferred-habitat model of the fixed income marked with a models of incomplete arbitrage on swap markets. This extended CIP condition allows us to derive international channels of monetary transmission. We adapt the preferred-habitat model to an open economy setting by considering segmentation along two dimensions: A domestic dimension, driven by term- and credit-structure, and an international dimension, driven by financial intermediation costs on swap markets. Arbitrage, which is subject to limited risk bearing capacity, is crucial in absorbing that segmentation. Our model closely follows Altavilla et al. (2015) for domestic arbitrage but 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, high-

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[1]The term refers to large foreign-currency arbitraging banks, that could, owing to their size, mark FX derivatives to market without considering conter-party default. See: https://ftalphaville.ft.com/2014/05/30/1866432/the-europe-based-flow-monster-is-under-siege/

light 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, a combination of policy asymmetries (US Dollar/ Euro interest rate differences) and market volatility, affects domestic pricing leading to widening return differences and worsening global dollar shortage. Limited arbitrage on swap markets, due to transaction costs, intermediation frictions, and a combination of risk and volatility cause persistence of CIP deviations. 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 short and long term markets possibly following differences in policy effectiveness across the term structure at the time. Analysis of policy attention measures, derived from GoogleTrends data, indicates a link to specific policies implemented at the time. A cointegration analysis of the term structure of the currency basis swap market suggests a link between volatility and frictions. In particular constant spreads between CCBS rates are rejected post 2012, suggesting that frictions are indeed time-varying and not constant as commonly assumed.

The remainder of this paper is structured as follows: The next section describes CIP failure and links it to the evolution of recent European and US monetary policy, followed by a brief review of the literature. Section 3 entertains the theoretical background, using preferred habitat theory, and highlights particular policy transmission channels. Our theoretical model leaves three main questions that we answer empirically: Is there transmission of policy imbalances onto FX swap markets, and is this via means or variances? We investigate policy transmission with EGARCH-in-Mean models in section 4. Are frictions, arising from market segmentation and risk constant or time-varying? Does volatility have an impact onto those frictions? We answer both questions in section 5 in an analysis of cointegration between CCBS rates. Section 6 offers conclusions and an outlook for further research.

2 CIP Failure

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

$$(1 + r_t) = \frac{F_t}{S_t}(1 + r_t^*), \tag{1}$$

where r_t denotes the yield on a domestic asset at time t, r_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

$$f_t - s_t \approx r_t - r_t^*. \tag{2}$$

2 is a no-arbitrage condition as, in the absence of frictions and exchange rate risk,[2] risk-less profits could be realised through cross-currency swaps. The resulting price of such swaps is closely related to the cross-currency basis, b,[3] which in the no-arbitrage case can be expressed as

$$b_t = r_t - (r_t^* + f_t - s_t) = 0.$$

From an arbitrageurs' perspective, some non-negative b implies an arbitrage opportunity. Assuming the domestic rates exceed foreign rates, ie. $r_t > r_t^*$ arbitrage is profitable if the interest spread is larger than the forward spread, $f_t^i - s_t < r_t - r_t^* \Rightarrow b_t = r_t - (r_t^* + f_t^i - s_t) < 0$. In other words: An increase in US dollar denominated returns leads to a shortage of US dollar liquidity and a negative USD cross-currency bases. b can in this respect be interpreted as the degree to which the CIP condition is violated. Violations persist and can because of 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.

2.2 Swap Markets and Monetary Policy Post GFC

The foreign currency swap market is vast. The combined outstanding volume of forward, FX-swap, and currency swap trades, making it the main locus of foreign currency arbitrage, reached more than USD78 trillion as of December 2018.[4] US dollars and euros are the most commonly traded currencies. All the more spectacular is hence the failure of its main no-arbitrage condition, covered interest parity, on the Eurodollar market.

In the aftermath of the great financial crisis CIP has been subject to frequent, persistent violations. Figure 1 gives the evolution of the 3m-5y USD/EUR CCBS and implied volatility of S&P 500 options (VIX) post 2008. Widening of CCBS, especially for short maturities, was associated with the combination of a widespread USD shortage and emerging counter-party credit risk on Swap markets during the GFC and the Eurozone debt crisis. Bases successively narrowed again, following liquidity provisions through central banks. CIP deviations re-emerged in 2014 (BIS (2015a)), despite relatively low market risk. Spikes in VIX, that could be observed in 2015 seem less clearly correlated with currency bases. Market risk does clearly not offer a sufficient explanation for CIP deviations. At the same time divergence in monetary policies increasingly affected FX swap market clearing (BIS (2015b)). Figure 2 plots US and European policy rate futures, fed-funds (FFUS) and Euribor

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[2]The cross-currency basis, b, implied by eq. (2) does not carry any foreign currency exchange rate risk, as this is hedged through the forward leg of the swap. In section 4.1 we will use an augmented CIP condition that introduces counter-party default risk, which is differend from the FX exchange rate risk present in uncovered interest parity.

[3]Underlying trades are cross-currency swaps, which are floating/floating swaps with each respective libor rates as benchmarks. In the covered no-arbitrage case, cross currency swaps imply eq. (2) and a non-negative cross-currency basis hence implies CIP failure.

[4]See: https://www.bis.org/statistics/d5_1.pdf

(FFEU) futures, which are used 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 early attempts of monetary contraction in Europe, policy expectations diverged from 2014 onwards. This is linked to a FED 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.
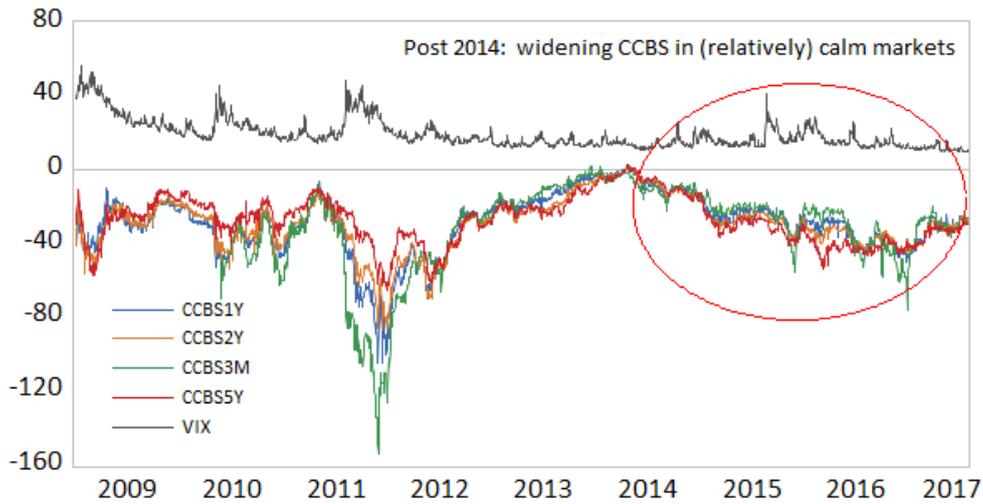

Figure 1: *CCBS Rates and Risk.* Figure plots 3M-5Y Cross-Currency Basis Swap rates (CCBS) (negative) with S&P500 implied stock options volatility (VIX).

Figure 2: *US and Eurozone Policy Rate Expectations.* Figure plots 1m ahead FED Funds (FFUS) and 1m EURIBOR (FFEU) futures.

2.3 Samples

Throughout the empirical sections of this paper (sections 5 and 6), we employ different partitions of the data. An overview of the partitioning of our data into several sub-samples is given in Fig. 3 below. Section 5 investigates the role of policy on explaining the CIP Puzzle. Following the literature on the CIP Puzzle, we focus on a sample covering the persistent widening of CCBS (01/2014-06/2016), which marks a time when policy asymmetry, measured by spreads between interest rate futures, was particularly strong. We split the sample further, excluding data post 11/2015 that contains several outliers in some regressions. In section 6 we answer questions regarding the co-movement between CCBS, abstaining from the effect of any other exogenous variables. For this purpose we extend the data on CCBS to obtain the longest available continuous series, which is from 05/2010 to 10/2017. We then partition the data into low and high-volatility regimes, based on VIX as indicator for market volatility.
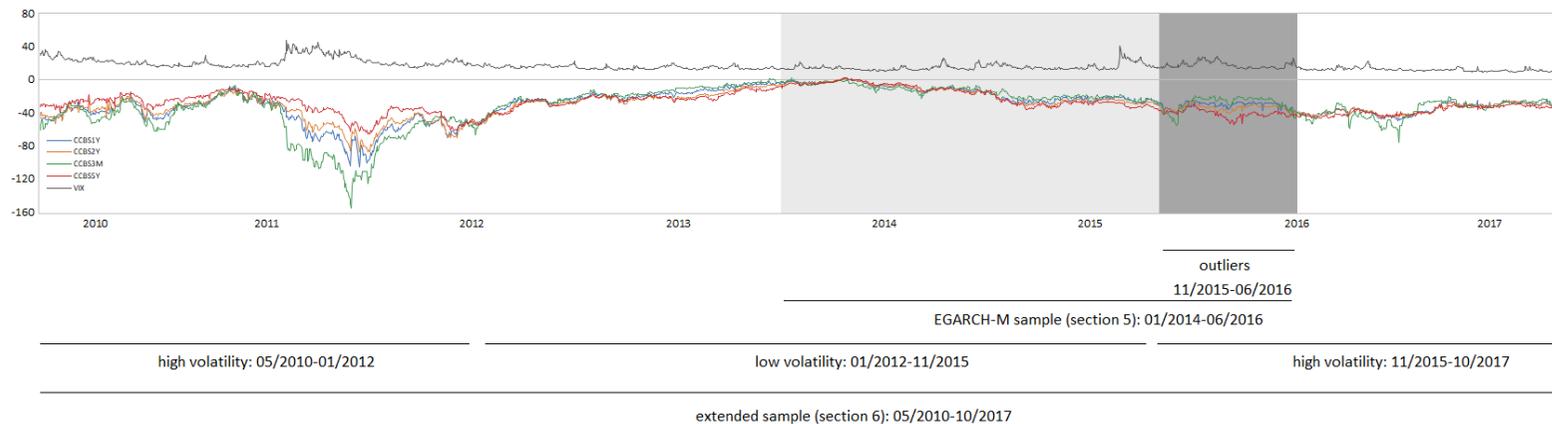
Figure 3: *Different Samples Investigated.* 3m-5y Cross-Currency Basis Swap rates (CCBS) plotted on bottom half, volatility measures VIX and FX volatility (FXV) on top half. Shaded areas highlight data used for EGARCH-M estimates (section 5), with dark shaded area giving sub-sample containing outliers and light shaded area a sub-sample excl. outliers.

3 Literature

Early contributions investigating post-crisis CIP failure highlight risk factors, which was plausible given the preceding global financial crisis (GFC). 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. Coffey et al. (2009) investigate CIP failure following the GFC. They link it to a mixture of adverse funding conditions and heightened counterparty risk, attributing 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 attempts to explain re-emerging CIP-deviations post 2014. 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 of bounded arbitrage on swap markets. Here, CCBS is a function of hedging demand and market-structural factors such as banks' ability to 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.

The role of the US dollar takes a centre stage in FX imbalances observed over the last decade for several reasons. There is strong evidence suggesting that US monetary policy drives global financial cycles (Rey (2015), Miranda-Agrippino and Rey (2015)), which implies periods of abundance and shortage of USD liquidity that are linked the the US monetary policy cycle. In a recent paper, investigating the relationship between US capital flows and the dollar exchange rate, Lilley et al.

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(2019) even claim an "exchange rate reconnect", initiated by post-crisis US foreign bond purchases. Arguably a large proportion of US foreign bond purchases is linked to monetary policy, particularly unconventional policy such as large scale asset purchases, causing portfolio rebalancing behaviour. Unconventional policies have taken a crucial role in central banks' policy reaction to the GFC and were hence discussed extensively in the recent literature [5]. It is all the more surprising that there is relatively little research explicitly evaluating the effect of recent policy imbalances on foreign exchange markets. Spill-over effects of such policies have been widely documented (Rey (2015), Miranda-Agrippino and Rey (2015), Wohlfarth (2018b), Wohlfarth (2018a), Gilchrist et al. (2019) among others). Globally, policy reactions to the GFC were relatively coordinated at first. But more recently this has become increasingly asymmetric. Arai et al. (2016) highlights the potential impact of global monetary policy imbalances on swap markets using descriptive evidence. He et al. (2015) find significant adverse USD credit supply effects of FED policy normalisation relative to other central banks, that have the potential to cause severe dislocations on FX swap markets. Papers investigating the relationship between policy and CIP failure are even scarcer: Du et al. (2017) and Borio et al. (2016) obtain evidence of policy effects on CIP using event studies on monetary policy announcements between 2010-15 and after 2014, respectively. Both indicate a widening effect of policy on long-term currency swap bases. This is unsurprising, given that policy, particularly monetary policy, arguably had a sizeable impact on bank balance sheets, and hence balance sheet costs. Similarly, one would expect policy to have an effect on banks' refunding operations and hence money market arbitrage.

In the theoretical literature unconventional policies initiated a vast amount of research into alternative channels of monetary transmission, which did not feature in traditional general equilibrium frameworks such as Christiano et al. (2005) and Smets and Wouters (2003). Such models particularly fail to produce sufficiently large term spreads on the fixed income market (Rudebusch and Swanson (2008)). Particular focus was on the impact of financial frictions on policy transmission. On fixed income markets a common explanation 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. Preferred habitat models assume heterogeneous agents: preferred habitat investors, whose demand is fixed to 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. Therefore, in the presence of segmented markets (or preferred habitats) risk acts like a transaction cost to arbitrage. This is affecting arbitrageurs' ability to mitigate market segmentation and introduces frictions into the model – an effect often referred to as the risk-premium channel of monetary transmission. Such a preferred habitat structure is applied in term-structure models, such as Hamilton and Wu (2012), assume market segmentation only along the term-dimension, which is omits credit risk. Altavilla et al. (2015) introduce a credit risk channel through including credit default risk probability into a preferred habitat framework. Investigating ECB's asset purchase program with

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[5]See Bhattarai and Neely (2018) for a comprehensive review.

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high-frequency event studies, they find that ECB announcements have 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.

Preferred habitat theory highlights the impact of risk and volatility as arbitrageurs' limited risk bearing capacity implies that both have an impact on the degree of segmentation that can be absorbed through arbitrage. Risk and volatility enter the model as quantity and price of risk, which empirically are observed as time-varying variance processes. The existence of such 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)). Volatility clusters for financial data are further typically skewed, as underlying uncertainty tends to be more sensitive to negative market movements. This effect is treated with leverage terms in exponential, EGARCH models (Nelson (1991)). Conditional volatility is largely ignored in the literature on CIP frictions. Frictions are typically assumed constant in models of swap market arbitrage and empirical contributions commonly suffer from employing relatively low frequency data (i.e. monthly or lower) and/or constant variance processes.

4   Model

To investigate how policy affects the failure of covered interest parity 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.

4.1   Pricing on FX Swap Markets

The cornerstone of CIP arbitrage is the cross-currency basis with maturity i, $CIP_{i,t}$, which forms a set of arbitrage bounds, $CIP_{i,t}^- \geq CIP_{i,t} \geq CIP_{i,t}^+$, such that,[6]

$$
\begin{aligned}
CIP_{i,t}^- &\equiv r_{i,t} - (r_{i,t}^* + f_{i,t} - s_t) \geq -\theta_t \rho \sigma_s^2 D_t^{XC} - c\left[(r_t^{REPO} - r_t) - (r_t^{*,REPO} - r_t^*)\right] \\
&- \left[(f_{i,t}^B - s_t^A) - (f_{i,t}^A - s_t^B)\right]/2 \\
CIP_{i,t}^+ &\equiv r_{i,t} - (r_{i,t}^* + f_{i,t} - s_t) \leq \theta_t \rho \sigma_s^2 D_t^{*,XC} + c\left[(r_t^{REPO} - r_t) - (r_t^{*,REPO} - r_t^*)\right] \\
&+ \left[(f_{i,t}^B - s_t^A) - (f_{i,t}^A - s_t^B)\right]/2,
\end{aligned}
\tag{3}
$$

where $r_{i,t}$ and $r_{i,t}^*$ are domestic and foreign yields, respectively, $f_{i,t}$ and s_t are forward and spot exchange rates, θ_t is a time-varying parameter governing counterparty credit default risk probability on forward swap markets, ρ gives the coefficient of absolute risk aversion, the exchange rate variance, σ_s^2, D_t^{XC} and $D_t^{*,XC}$ give

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[6]See appendix A.1 for details.

domestic and foreign hedging demand shocks, and c gives a fraction of CIP arbitrage funded via REPO markets, with r_t^{REPO} and $r_t^{*,REPO}$ 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, $r_{i,t}$ and $(r_{i,t}^* + f_{i,t} - s_t)$, 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.

θ_t plays a crucial role in introducing arbitrage frictions. Owing to the high degree of collateralisation, swaps are usually considered default-risk free trades. But cross-currency basis swaps carry the residual risk of a counter-party being stuck with foreign-currency denominated collateral (Sushko et al. (2017)). 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. θ_t therefore introduces costs to (hedged) foreign currency balance sheet exposure. Swap market clearing implies that the demand for FX forward hedges corresponds to arbitrageurs' foreign currency exposure. θ_t then implies that arbitrage opportunities, and corresponding hedging demand shocks, need to be sufficiently large to overcome costs from balance sheet exposure. This effectively introduces bounds around CIP that need to be overcome for arbitrageurs to enter a swap position.

4.2 Domestic Fixed Income Pricing

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, r_t^i are priced as[7]

$$r_{i,t} = \frac{1}{n}\sum_{j=0}^{n} E_t(r_{t+j}) + \frac{1}{n}\sum_{j=0}^{n} E_t\left(\gamma'(\mu + \Phi X_{t+j})\right) \frac{1}{n}\sum_{j=0}^{n} E_t\left((\bar{b}_i' + \gamma')\Psi\lambda_{t+j}\right)$$
$$-\frac{1}{2}(\bar{b}_i' + \gamma')\Psi(\bar{b}_i + \gamma),$$

and

$$r_{i,t}^* = \frac{1}{n}\sum_{j=0}^{n} E_t(r_{t+j}^*) + \frac{1}{n}\sum_{j=0}^{n} E_t\left(\gamma^{*'}(\mu^* + \Phi^* X_{t+j}^*)\right) \frac{1}{n}\sum_{j=0}^{n} E_t\left((\bar{b}_i^{*'} + \gamma^{*'})\Psi^*\lambda_{t+j}^*\right)$$
$$-\frac{1}{2}(\bar{b}_i^{*'} + \gamma^{*'})\Psi^*(\bar{b}_i^* + \gamma^*),$$

(4)

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, Ψ, the market price of risk, λ, and bond pricing and credit-risk coefficients, $\bar{b}_i'$ and γ. The dynamics of fixed income arbitrage enter through the market price of risk,

$$\lambda_t = \rho \sum_{i=1}^{N}(S_t^i - \xi_t^i)(\bar{b}_i + \gamma),$$

(5)

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[7]See appendix A.2 for the corresponding arbitrage portfolio optimisation.

which is a function of risk aversion, ρ, arbitrage demand, given as difference between local asset supply, S_t^i, preferred habitat demand, ξ_t^i, and the pricing coefficients $\bar{b}_i$ and γ.

4.3 Monetary Policy Transmission

Domestic Transmission Channels Monetary policy enters 3 through its effects on domestic fixed income pricing or through its effects on CIP arbitrage. For the former, it affects domestic yield pricing in 4 through either asset supply, S_t^i, 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 comes in as policy asymmetries affect relative prices of foreign to domestic assets. This induces portfolio rebalancing behaviour and therefore changes to foreign currency denominated asset exposure, which in turn implies effects on 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[8].

Policy and the Currency Basis Since policy asymmetries affect relative prices between domestic and foreign assets, yield spreads, given in (3) directly transmit onto $CIP_{i,t}$. Were (3) 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, (3) is bounded away from zero and hence $CIP_{i,t}$ can be non-zero and return differentials are tolerated on swap markets. The impact of policy on $CIP_{i,t}$ stems from the degree to which policy causes rate differentials and hence opens arbitrage opportunities on swap markets, which causes shocks to swap demand, D_t^{XC}. This implies that any asymmetries of the factors that affect domestic and foreign yields in (2) lead to a widening of $CIP_{i,t}$, which, following the argument of (Sushko et al. (2017)), the frictions in (3) prevent from closing. In this setting domestic policy has spillover effects, and hence affects foreign assets. Similarly, policy has an impact on asset

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[8]Participating 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.

volatility for both domestic and foreign assets. There is therefore an effect of policy on FX volatility, σ_s^2. The CIP arbitrage channel gives policy also a direct impact on the cross currency basis through its effects on arbitrage liquidity.

To expose aforementioned transmission channels we can write (4) in terms of premiums over a risk less benchmark, [9]

$$r_{i,t} = \frac{1}{T} \sum_{i=1}^{T} \mathbb{E}\overline{r}_{t+i} + CP(\boldsymbol{x}, \iota) * VP(\gamma, \lambda(\sigma, \omega(S, \xi), \overline{b}, \gamma), \Psi), \qquad (6)$$

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

$$CIP_{i,t} = (\frac{1}{T} \sum_{i=1}^{T} \mathbb{E}\overline{r}_{t+i} - \frac{1}{T} \sum_{i=1}^{T} \mathbb{E}\overline{r}_{t+i}^*) + (CP - CP^*)(VP - VP^*),$$
$$+ \theta_t \rho \sigma_s^2(\Psi, \Psi^*) D_t^{XC}(r_t, r_t^*) + \Lambda(r_{i,t}, r_{i,t}^*, r_{REPO}, r_{REPO}^*, f^A, f^B), \qquad (7)$$

where Λ denotes swap market arbitrage frictions and collects terms affecting wholesale refunding and swap market liquidity. Accordingly, policy feeds into (3) directly through rate differentials as well as indirectly through its effects on CIP arbitrage.

5 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.

5.1 Data

We employ a sample of US and European daily fixed income, foreign exchange and Google search data from January 1st 2014 - June 30 2016. The data is chosen in order to capture policy asymmetries between the ECB and the FED, which were particularly strong at the time. We further estimate results for a sub-sample separately due to the presence of outliers after November 2015 [10].

Figure 3 plots the evolution for CCBS rates across maturities, together with two volatility measures, VIX and FX volatility (FXV), and residuals obtained from the estimation of EGARCH-M models. 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 3m and 5y bases: Initially, 3m CCBS were widening the most,

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[9]For the ease of exposition, we omit the respective equation for y^*, which is equivalent.

[10]In 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 it's EAPP by less then expected as well early misreporting of the policy decision by the Financial Times. Both is likely to have contributed to abnormally high volatility on markets.

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whilst the 5y CCBS was narrowest. This situation is reversed towards the end of the sample. This change in the term-structure of CCBS rates indicates changes to market segmentation over time. There appears to be some link to changes in volatility and GARCH residuals exhibit a series of substantial outliers towards the end of the sample. The latter motivates the estimation of a subsample that likely gives more efficient estimates.
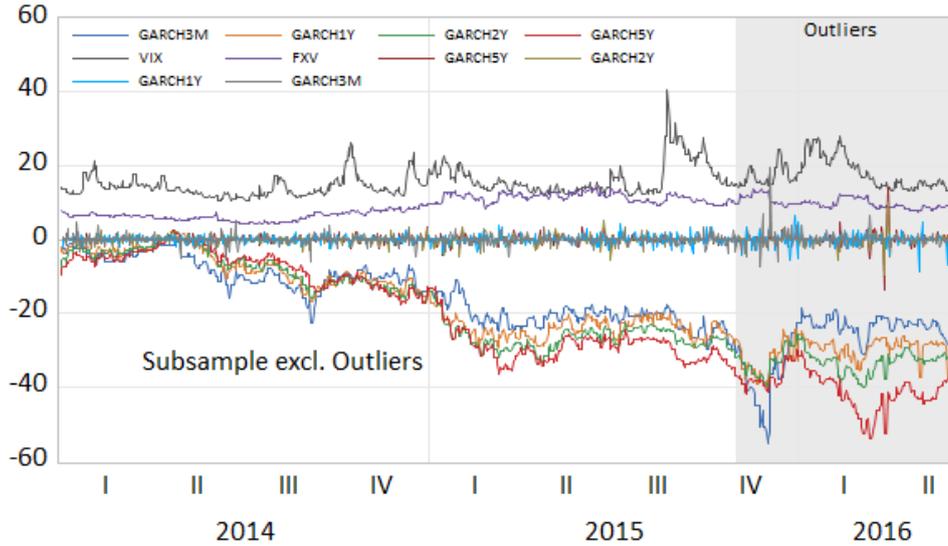
Figure 3: *3m-5y CCBS Rates and Volatility.* 3m-5y Cross-Currency Basis Swap rates (CCBS) plotted on bottom half, volatility measures VIX and FX volatility (FXV) on top half, and residuals obtained from estimated EGARCH-M models, GARCH3M-GARCH5Y, in centre.

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 hand.
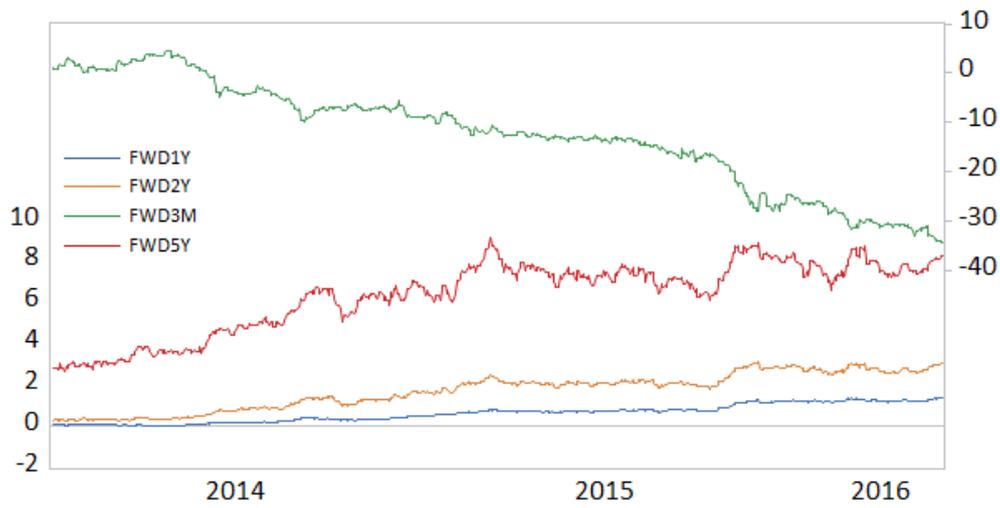
Figure 4: *Forward Spreads.* FWD3M (right), FWD1Y-FWD5Y (left).

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. below.
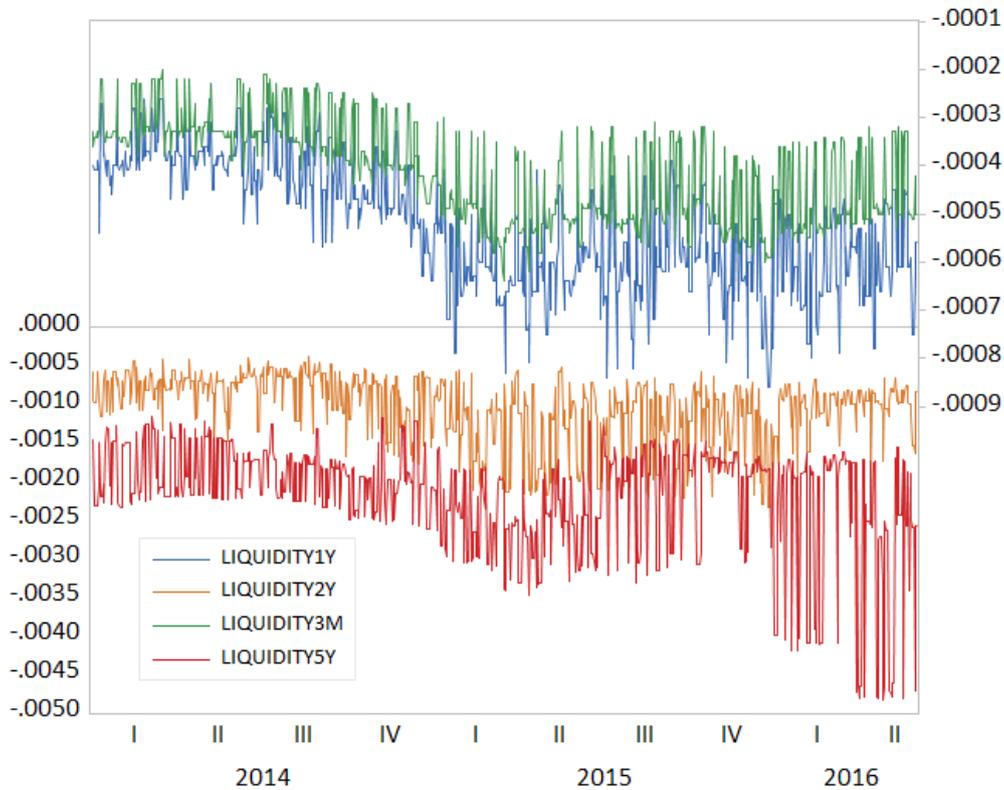
Figure 5: *Swap Market Liquidity.* LIQUIDITY3M and LIQUIDITY1Y (right), LIQUIDITY2Y and LIQUIDITY5Y (left).

Counter-party credit risk measures for US and Eurozone are plotted in Figure 6. There are several sharp imbalances 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 likely linked to US policy rate increases at the time.

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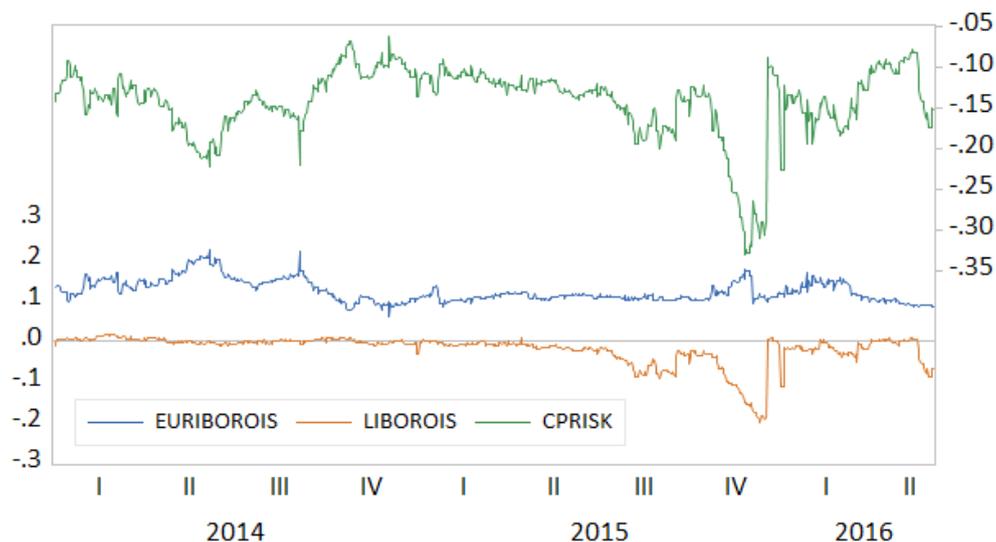
Figure 6: *Counter-Party Credit Risk.* Figure plots counter-party credit risk, CPRISK and it's constituents, EURIBOR-OIS and LIBOR-OIS spreads

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 policy changes in 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 raise to the existence of volatility premia.
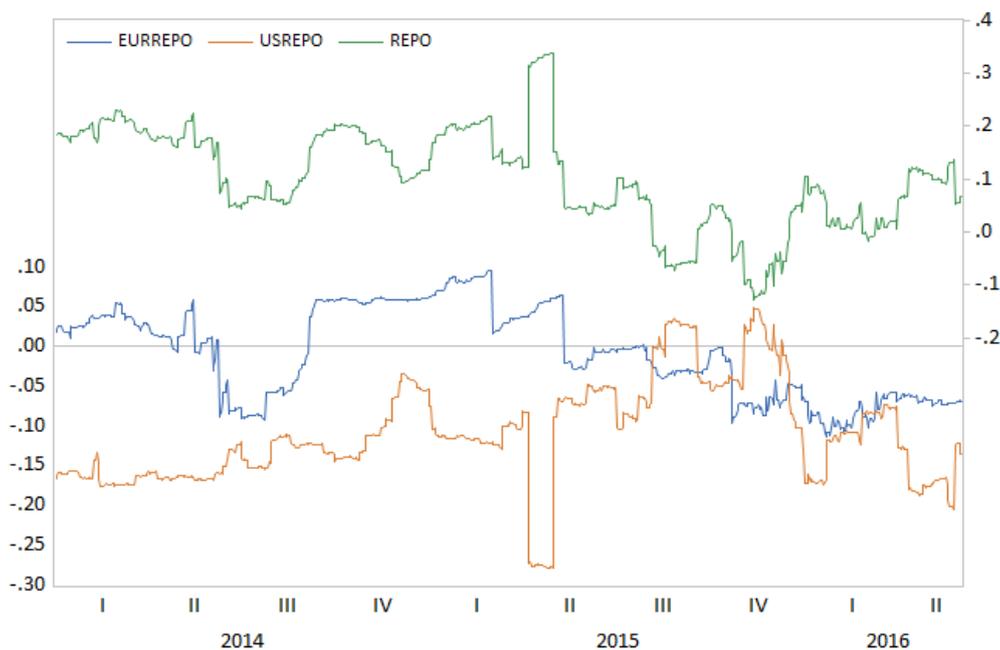
Figure 7: *REPO-Spreads.* Figure plots constituents of REPO, 3m EURIBOR-REPO (EURREPO) and LIBOR-REPO (USREPO) spreads

Figure 8 gives the evolution of policy attention, $MPSI$, (Wohlfarth (2018b)) decomposed by it's US and European constituents. Policy attention is measured based on Google Trends search volume indices for policy related search terms. Both indices spike around a set of identified policy relevant events and display considerable co-movement, which is unsurprising given that both, policy spill-overs and reaction to global shocks a reaction of attention to both central banks. There are, however, differences in timing and magnitude of some of the shocks.[11]

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[11]See Appendix C for details on index construction and identified events.
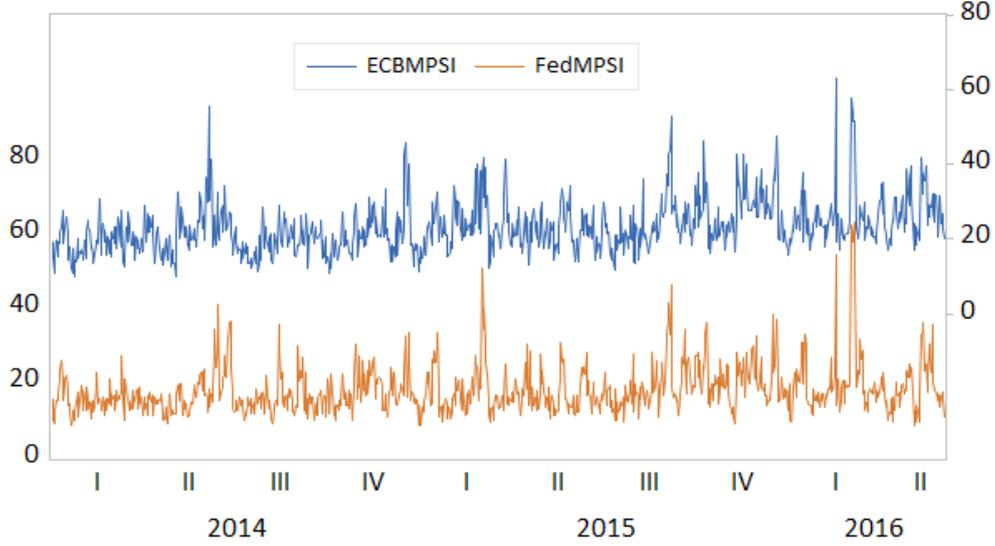
Figure 8: *Policy Attention.* Figure plots constituents of our policy attention measure (MPSI), US (FEDMPSI) and European policy attention (ECBMPSI).

5.2 EGARCH-in-Mean Models of Cross-Currency Bases

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

$$CIP_{i,t} = x'_{i,t}\beta + \nu_{i,t} \tag{8}$$

where $\quad x'_{i,t} = \begin{pmatrix} 1, & \log h_{i,t}, & FF_t, & FWD_{i,t}, & REPO_t, & Liquidity_{i,t}, & CIP_{i,t-1} \end{pmatrix},$

and $\quad \nu_{i,t} = \varepsilon h_{i,t}^{1/2}, \quad \varepsilon \sim IID(0,\Sigma) \quad$ and

$$\log h_{i,t} = c_{i,0} + c_1 h_{i,t-1} + c_2 |\frac{\nu_{i,t-1}^2}{h_{i,t-1}}| + c_3 \frac{\nu_{i,t-1}^2}{h_{i,t-1}} + c_4 VIX_{i,t} + c_5 FXV_{s,t} + c_6\theta_{i,t} + c_6 MPSI_{i,t}.$$

β is a 6×1 coefficient vector, $CIP_{i,t}$ denotes the EUR/USD CCBS rate, for swaps with maturity $i = $ 3m, 1y 2y, and 5y. FF_t gives the difference between front-month Fed-Funds and EURIBOR futures for the US and the Eurozone, $FWD_{i,t}$ is the forward spread, given as difference between spot and respective forward exchange rates, and $MPSI_t$ the difference in policy attention indices, using Google search data.We further control for the wholesale refunding liquidity premiums, captured through the LIBOR-REPO spread, $REPO_t$, a swap market liquidity premium, $LIQUIDITY_{i,t}$, given by bid-ask spreads on FX spot and forward markets, and a counter-party risk

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premium, $\theta_{i,t}$, captured through OIS-LIBOR spreads. VIX_t gives implied volatility of S&P 500 options as a general proxy for market risk and $FXV_{s,t}$ is implied volatility on USD/EUR foreign exchange options as a proxy for FX market risk. Models assume stationarity and variables enter in first differences.

5.3 Effects of Policy Asymmetry

In line with the previous section we investigate estimates for the effect of asymmetry, i.e. differentials in interest rate futures. Table 1 gives estimates obtained from the full sample and a sub-sample that excludes outliers. Our main findings are based on the latter sample, given the otherwise likely outlier bias. We report both sets of estimates for robustness purposes.

Table 1: CCBS Regressions

Mean	3m	1y	2y	5y	3m	1y	2y	5y
	Full Sample 01/2014-06/2016				Excl. Outliers 01/2014-11/2015			
GARCH	-0.077	-0.038	-0.096 *	-0.142 *	-6.751 ***	-0.205 *	-0.134 *	-0.184 *
C	-0.042	-0.013	-0.055	-0.050	-1.692 ***	-0.030	-0.097	-0.104
FF	0.047 *	-0.040	-0.099 ***	-0.054 **	0.079 ***	0.012	-0.084 ***	-0.108 ***
(S-FWD)	0.002 ***	-7.948 ***	-4.482 ***	-1.444 ***	0.007 ***	-10.426 ***	-4.389 ***	-1.267 ***
REPO	-0.001	0.002	-4.921 ***	-4.079 ***	-0.005	-0.023	-0.084 ***	0.642
LIQUIDITY	-10.604 ***	3.552	-67.8547 *	105.917 ***	2.727	3.565	-0.716 *	-0.076 ***
CIP_{t-1}	0.054 **	-0.057 *	0.057 **	0.039	0.683 ***	-0.060	0.068 **	0.042
Variance								
C(8)	-0.328 ***	-0.063	-0.306 ***	-0.232 ***	-0.233 ***	-0.276 ***	-0.333 ***	-0.463 ***
ARCH	0.161 ***	0.402 ***	0.022	0.046	-0.003	0.395 ***	-0.092	0.233 ***
Leverage	-0.028	0.037	0.274 ***	0.271 ***	0.099 ***	0.114	0.224 ***	0.254 ***
GARCH	0.032	-0.707 ***	0.547 ***	0.368 ***	0.063 *	-0.066	0.476 ***	0.360 **
VIX	-0.079 **	0.069 ***	0.106 ***	0.066 *	-0.002	0.077	0.052	0.033
FXV	-0.120	0.091	0.453 ***	0.314 ***	0.002	-0.033	0.272 **	0.227
CPRISK	2.463	1.840	12.483 ***	14.204 ***	0.376	17.601 **	-4.414	-3.322
MPSI	0.045 ***	-0.006	-0.001	-0.021 *	0.001	-0.000	0.006	-0.006
t-DoF	3	3	3	3	3	3	3	3
R2	0.018	0.017	0.081	0.070	0.184	0.035	0.081	0.064
SER	1.207	1.290	0.819	0.998	0.895	0.973	0.726	0.756
BIC	2.650	2.872	2.098	2.385	2.417	2.671	2.013	2.203
DW	2.002	2.214	1.940	2.008	2.125	2.247	2.038	1.953

Notes: Table gives estimates for regressing eq (8), where $i = 1m, 1y, 2y, 5y$. The left for columns give results based on a sample including detected outliers (02/01/2014-30/06/2016), the right for columns consider a sub-sample that excludes outliers (02/01/2014-01/11/2015). Dependent variables are 3m-5y CCBS rates. Estimation of all models via maximum likelihood assuming t-distributed errors 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: $^* < 10\%, ^{**} < 5\%, ^{***} < 1\%$.

Full Sample including Outliers Estimates are given on the left half of table 1. 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.[12] 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 effects, there is evidence for policy transmission via the aforementioned volatility channel. The fact that this

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[12]For all maturities except 1y there is no Granger-causality from dependent to explanatory variables. Granger-causality tests for the one year basis suggests feedback to explanatory variables and coefficients might be biased as a result. See appendix B2 for details.

evidence appears for longer CCBS maturities may be due to MPSI capturing more unconventional policies, which had a greater impact on capital markets. MPSI enters negatively on capital markets, suggesting a mitigating effect of policy on uncertainty, and positively on money markets, again giving different dynamics for money and capital markets.

Generally, 3mth CCBS appears to be almost entirely driven by market liquidity. Money market dynamics are typically sensitive to traded flow volumes, rendering this result unsurprising. 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 in line with the shift to unsecured money market funding operations, documented in Rime et al. (2016). The shift away from wholesale refunding operations could further indicate adverse policy effects on money markets at the time: Beaupain and Durré (2016) investigate 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 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 domestic expansions helped closing the cross-currency basis on capital markets (and hence international policy asymmetries contributing to it widening again), effective contractions on money markets had a widening impact on the cross currency basis and 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.

Sub-Sample excluding Outliers Employing a sample that excludes outliers after November 2015 (right half of table 1) 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 FXV on capital markets and by $CPRISK$ 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 $Liquidity$, 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.

Robustness We consider two extensions for robustness purposes: The inclusion of Economic Policy Uncertainty, EPU, (Baker et al. (2016)) in all models and of bank credit default swap, CDS, indices for 5y CCBS[13] as an alternative measure for risk. Results are summarised in tables 9 and 10, Appendix B.3. Including further control variables confirms findings on direct policy impacts as well as the impact of volatility for 3m CCBS using the restricted sample. For longer maturities and estimates based on the full sample, GARCH-in-Mean coefficients are insignificant. European bank CDS have a significant effect on the widening of the 5y basis, whilst US CDS are significant in the full sample only. EPU enters variances significantly in almost all models. Coefficient sizes are relatively small. Controlling for exchange trading hours validates results for policy measures in regressions using longer maturities. Results on GARCH-in-Mean effects are generally robust.

5.4 Decomposition of Policy Effects

We decompose policy measures, FF and $MPSI$, into respective constituents to investigate relative contributions of observed policy effects. Results are given in table 2 below, with the restricted sample on the left half and the full sample on the right half of the table.

Table 2: CCBS Regressions Decomposing US and European Policy Measures

Mean	3m		1y		2y		5y		3m		1y		2y		5y	
		Excl. Outliers 01/2014-11/2015								Full Sample 01/2014-06/2016						
FF_{EU}	-0.107	***	-0.025		0.092	***	0.105	***	-0.072	**	0.031		0.109	***	0.097	***
FF_{US}	-0.033		-0.036		-0.163	**	-0.192	**	-0.329	***	-0.062		-0.097	**	0.048	
Variance																
$MPSI_{EU}$	-0.001		0.011		0.026	**	0.004		-0.028	**	0.012	***	0.027	**	0.021	*
$MPSI_{US}$	0.002	**	0.016		0.035	**	-0.010		0.071	***	0.006		0.011		-0.013	
t-DoF	3		3		3		3		3		3		3		3	
R2	0.192		0.028		0.062		0.066		0.003		0.014		0.075		0.06	
SER	0.891		0.977		0.734		0.756		1.216		1.293		0.821		0.758	
BIC	2.424		2.685		2.024		2.222		2.646		2.880		2.108		2.193	
DW	2.137		2.26		1.990		1.955		1.989		2.228		1.941		1.951	

Notes: The table gives estimates for policy measures, decomposed into US and European constituents. Results are otherwise based on previous specifications (see Table 1), but other variables have been excluded for the ease of exposition. Dependent variables are 3m-5y CCBS rates. Estimation of all models via maximum likelihood assuming t-distributed errors 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: * $< 10\%$,** $< 5\%$,*** $< 1\%$.

In terms of direct effects, widening currency bases appear to be driven by the US for both samples: almost all coefficients on FF_{US} are negative whilst coefficients on FF_{EU} are positive for longer maturities, indicating a narrowing on respective cross currency bases. Effects are generally significant, apart from one year maturities and the coefficient on FF_{US} in the 3m basis in the restricted and the 5y basis in the full sample. Respective coefficients indicate a shift from longer to shorter dated maturities, whilst the opposite effect is observable for the Eurozone. In terms of

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[13]The choice to control for CDS for 5y CCBS only is based on limited data availability for shorter maturities.

variances we can observe a shift of policy attention from capital to money markets in the US and to both, the very short and long end of considered tenors in Europe. This is unsurprising, indicating the increasing importance of policy rate-setting following the lift-off and successive increases in the FED Funds rate, whilst with the implementation of negative deposit rates and extensive quantitative and qualitative easing measures ECB interventions appeared to have affected both ends of the term structure. However, results have to be interpreted with caution owing to detected outliers in the full sample.

6   Volatility and the Term Structure of CCBS Rates

As figure 3 shows, different CCBS rates clearly move together. Indeed, based on Johansen cointegration tests and depending on assumed determistic terms and chosen test statistics, there are between 2 and 4 cointegrating relationships between CCBS, for data on the whole available post-crisis period (2008-2018). However, the nature of that relationship appears to be changing over time. Data before 2012 unambiguously suggests 2 cointegrating relationships, there are between 3 and 4 cointegrating relationships for 2012-2015, and almost unambiguously 1 cointegration relationship after 2015.[14] Visual inspection of the data confirms the changing relationship between variables. Following the model in section 3, this could be symptomatic for CIP arbitrage frictions that may have increased due to the presence of a volatility premium. To investigate this, we examine effects of market volatility on the relationship between CCBS rates. For this, we first consider a longer sample from 2010 to late 2017, which we then partition into high and low volatility regimes based on global stock options volatility (VIX). We then analyse principal components for the different samples and cointegration between CCBS rates in a VECM framework.

Figure 9 plots CCBS rates and VIX for the sample considered. The shaded area indicates the high volatility samples.

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[14]For the last sub-sample the trace statistic in a model assumning quadratic trends and intercepts indicates two cointegrating vectors. All remaining test statistics indicate one.
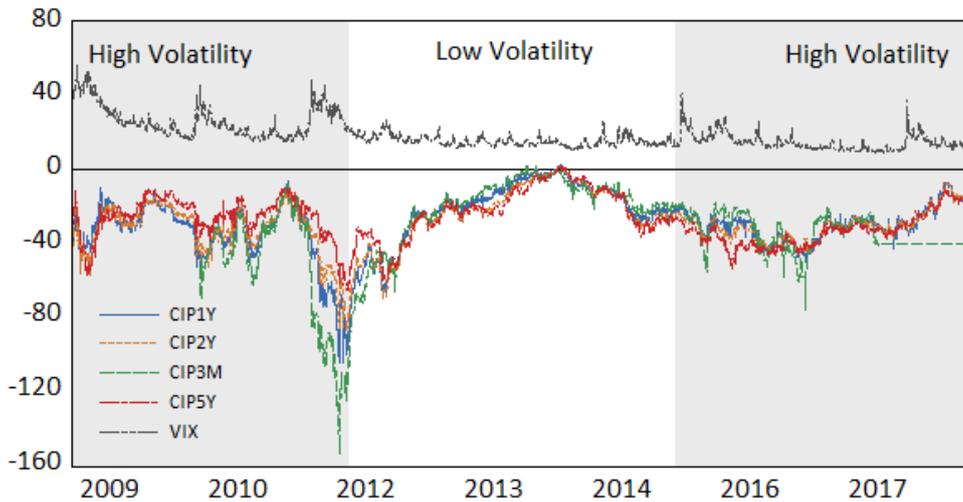
Figure 9: *Volatility and CCBS.* The figure plots VIX along with CCBS across maturities. Shaded areas highlight high-volatility regimes.

The dispersion of CCBS appears to be linked to market volatility. This is particularly strong in the second half of 2011, which is likely due to the Eurozone crisis, as well as the last quarter of 2015, that includes the outliers discussed above. The mere existence of changes in dispersion across CCBS tenors is striking and at odds with the common assumption of constant transactions costs. Whilst the existence of some non-negative cross-currency basis could be explained with simple market-structural frictions, such as transaction costs, the spreads between CCBS rates of different maturities indicates the presence of market segmentation. That this dispersion is time-varying and linked to volatility is in line with the presence of a volatility premium.

6.1 Principal Components

Since CCBS rates indicate a deviation from no-arbitrage conditions they should, in the absence of frictions, such as market segmentation and intermediation frictions, be zero. Observed bases hence indicate the presence of frictions. In the absence of segmented markets these frictions should be the same along the term structure, CCBS rates should thus be similar and we should not be able to observe more than one principal component. Conversely, the presence of more than one principal component indicates an impact of market segmentation on fx swap market frictions. Following our model, market segmentation is exacerbated through volatility due to the limited risk-bearing capacity of arbitrageurs. To investigate the impact of volatility on frictions through market segmentation, we therefore first compare principal components for the samples considered. The proportion of variances explained through the first three principal components are summarised in table 3 below.

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Table 3: First Three Principal Components

Factors	Variance Proportion		
	Pre 2012	2012-2015	Post 2015
1	0.9497	0.9593	0.7104
2	0.0453	0.0324	0.2629
3	0.0044	0.0063	0.0235

Whilst both, the pre-2012 sample and the 2012-2015 sample yield similar results, there is a striking difference between the post-2015 sample: More than a quarter of the variance is explained by a second factor and more than 2% by a third factor. This is at odds with the absence of market segmentation and strikingly coincides with an increase in volatility, that coincides with diverging policy and is following period of relatively calm markets.

6.2 VECM of the Relationship between CCBS

Following preferred-habitat theory, frictions should further be time varying: Limits to arbitrage takes a crucial role in explaining frictions and is largely driven by risk, particularly volatility. We investigate both, the time-varying nature of frictions and the relationship between CCBS tenors and volatility with an analysis of the cointegration relationship between CCBS rates. Accordingly, we employ a vector error correction model (VECM) as

$$\Delta y_t = \boldsymbol{A_0} - \boldsymbol{\alpha}(\boldsymbol{\beta'}y_{t-1} + ct) + \sum_{i}^{p-1} \boldsymbol{\Gamma_i}\Delta y_{t-1} + \varepsilon_t,$$

where y_t is a 1×4 column vector of the 4 CCBS rates. $\boldsymbol{\beta}$ is a 3×4 matrix of identifying restrictions

$$\boldsymbol{\beta} = \begin{pmatrix} 1 & -1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix}.$$

The restrictions implicitly treat the system of CCBS-rates analogue to a term structure, so that the system has stationary spreads, $\boldsymbol{\beta}$, which are chosen relative to the 1Y CCBS rate as a benchmark. $\boldsymbol{\alpha}$ gives a 3×4 matrix of adjustment coefficients. We test the restrictions using the LR test for binding restrictions. Note that a non-segmented market implies stationary spreads of zero between CCBS rates, which is contained in the restrictions. Therefore a test of binding restrictions on $\boldsymbol{\beta}$ implies a test for market segmentation.

Table 4: Volatility and Cointegrating Vectors

	2010 - 2012			Cointegrating Vectors 2012 - 2015			2015 - 2018		
	β_{1Y}	β_{2Y}	β_{5Y}	β_{1Y}	β_{2Y}	β_{5Y}	β_{1Y}	β_{2Y}	β_{5Y}
α_{3M}	-0.054	-0.039	-0.038	-0.051	-0.079	0.030	-0.007	0.020	0.003
	[-2.274]	[-0.330]	[-0.704]	[-3.762]	[-1.340]	[1.318]	[-1.187]	[0.365]	[0.128]
α_{1Y}	0.119	0.180	0.063	0.033	0.224	-0.060	0.015	0.148	-0.011
	[5.476]	[1.632]	[1.258]	[2.093]	[3.229]	[-2.25]	[2.723]	[2.775]	[-0.478]
α_{2Y}	-0.028	-0.631	0.260	-0.049	-0.142	0.042	-0.001	-0.113	0.047
	[-1.43]	[-6.260]	[5.624]	[-3.673]	[-2.422]	[1.861]	[-0.391]	[-2.893]	[3.686]
α_{5Y}	-0.010	-0.100	0.012	-0.023	0.081	-0.053	-0.003	0.059	-0.030
	[-0.663]	[-1.293]	[0.357]	[-1.872]	[1.476]	[-2.495]	[-0.823]	[1.460]	[-1.657]
LR	6.965			37.26			29.87		
p(LR)	0.072			0.000			0.000		
k	59			59			75		

Table 5 gives the adjustment coefficients, α_y, on the cointegrating vectors (CV), $\boldsymbol{\beta}$, where the restrictions given above are applied. The restrictions are clearly rejected for the post 2012 and post 2015 samples and cannot be reject at a 5% confidence level for the pre-2012 sample. This indicates that the CCBS market became more segmented after 2012. This is in line with descriptive evidence and the literature, whereby CIP deviations were following risk measures until 2012 followed by a breakdown of that relationship thereafter. The breakdown of this relationship is likely explained by the global policy environment at the time, which, following the evidence above, had a significant impact on FX swap markets.

The adjustment coefficients show most significant feedback in the low volatility sample. Between 2012 and 2015 seven out of twelve adjustment coefficients fed back significantly to the CVs, compared to each four in the other samples. This suggests that there is generally more adjustment to cointegrating relationships between CCBS rates in the absence of volatility, which indicates some effect of volatility on the cointegration between CCBS rates. An exception to this is the adjustment of 2Y CCBS to the third CV, which normalises to the spread between 1Y and 5Y CCBS. The same adjustment coefficient turns insignificant in the low volatility sample, where the adjustment of the 2y CCBS with respect to the first (3m/1y) cointegrating vector is feeding back significantly. This suggests that volatility shifts feedback from short to long maturities. The adjustment of the 5Y CCBS to the first CV confirms this (albeit insignificantly): the feedback is largest in the low volatility sample. In the 5y basis we can also observe a change in direction of its feedback to 2y/1y and 5y/1y spreads. This corresponds with narrowing of short tenor CCBS (3m and 1Y) relative to 2y and 5y CCBS pre 2012. In other words: The CCBS curve was inverted pre 2012 and resembled a normal term-structure thereafter. This confirms previous evidence on different dynamics between short and long maturities on FX swap markets, which may be affected by policy as well: At shorter maturities CCBS are mainly driven by risk-factors, which receded between 2012 and 2015. At the long end, CCBS are driven by more fundamental and market structural factors, as well as unconventional monetary policies, which are then exacerbated by market volatility. This cointegration analysis of FX swaps therefore provides evidence for the combined role of risk, structural factors, and policy in causing recently observed CIP failure.

7 Outlook and Conclusions

We investigate post-crisis failure of covered interest parity. In a theoretical framework, we combine preferred habitat theory of domestic fixed income pricing with a model of FX swap market frictions. A model of Eurodollar CIP deviations, derived from our framework, shows how a shortage of dollar liquidity, caused by policy asymmetries, can lead to failure of CIP in the presence of arbitrage frictions. Returns entering CIP are priced domestically on segmented markets. Preferred habitat theory explains pricing on segmented markets in a heterogeneous agent setting, where agents are either preferred habitat investors, with price-inelastic demand, or arbitrageurs, who exploit and thereby absorb resulting market segmentation. In this setting the degree of segmentation, and hence pricing, depends on arbitrageurs' activity on the market. This in turn is subject to their limited risk bearing capacity, i.e. by the amount of risk arbitrageurs can absorb. Risk, as a combination of quantity and price of risk, is time-varying and hence market segmentation, the source for frictions in our model, should be time-varying. Policy enters the model directly through its effect on policy rate expectations and indirectly through effects on risk and market segmentation. On FX swap markets, arbitrage carries counter-party risk through foreign currency denominated collateral. This introduces intermediation costs arising from arbitrageurs' costly balance sheet exposure, captured by corresponding hedging demand, and thereby exacerbates domestic pricing effects. In this setting direct policy effects and volatility cause return differentials that result in a global dollar shortage. Arbitrage frictions on FX swap market lead to persistence of imbalances. Our model therefore suggests that deviations from CIP are caused by a combination of policy, market structure, 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.

Empirically we tackle three main questions raised by our model. The first question concerns policy transmission onto CIP, which could be direct via rate expectations or indirect via variance processes. We investigate transmission channels with EGARCH in mean estimates in models of CCBS for different maturities. Here policy enters means directly through its effect on rate setting expectations, which we measure as the spread between FED-Funds and EURIBOR futures. Indirect effects are captured in variance processes through policy attention measures, based on Google-Trends data, and several risk and volatility measures. GARCH in mean coefficients estimate the feedback effect of volatility onto means, which according to our model are affected by market segmentation and volatility. We control for transaction costs such as market and wholesale liquidity. In a robustness exercise, we further control for effects of policy uncertainty, and bank CDS as well as for differences in exchange trading hours. We find that both policy and volatility has significantly contributed to the failure of CIP. Swap market volatility is mainly driven by risk, both counterparty and market risk. The evidence suggests different dynamics for short maturities of CCBS, which appear to be mainly driven by volatility premia. Decomposing policy attention measures indicates that frictions are driven by both ECB and FED for short tenors and largely by the FED for longer maturities. There is further evidence indicating a shift of policy attention to the short end of the term structure in the US and both the very short and long ends in Europe, which is in line with respective policy interventions. These results show that, when explicitly accounting for conditional volatility, foreign exchange swap markets are significantly

affected by policy-imbalances and are subject to volatility premia, resulting from market segmentation. A combination of counter-party credit risk, market volatility and uncertainty, as well as policy affect this volatility channel. The impact of such risk channels is underestimated in models failing to explicitly model conditional variance processes.

The remaining two questions relate to the presence of time-varying frictions and a link between volatility and frictions. We answer both through investigating the relationship between CCBS rates using principal component analysis and a VECM framework for different volatility regimes. Employing an extended sample from 2010-2018, our findings indicate the presence of a second factor after 2015 as well as an increase in market segmentation after 2012. This marks a time when risk factors became insufficient in explaining observed CIP failures and policy rate expectations drifted apart. Analysing adjustment to an imposed constant term-structure provides further evidence for a relationship between volatility and market segmentation. Again effects differ across maturities: Whilst short dated CCBS continued to be driven by risk factors post 2012, CCBS carrying longer maturities were affected by the increasingly asymmetric policy environment.

These results have important policy implications on the impact of policy imbalances on foreign exchange market clearing. In particular, our findings shed light on some, potentially unintended, adverse effects following the introduction of negative deposit rates and shows substantial effects of both, US policy rate increases and large scale asset purchases in Europe. More generally our findings highlight the impact of volatility and uncertainty on market returns. 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. Considering high-frequency data in conditional volatility models is crucial here as effects through volatility are otherwise easily overlooked, underestimating the impact of risk in general.

Our 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. Policy measures could be further extended to cater for the effects of unconventional policies on the longer end of yield curves. 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.

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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

$$
\begin{aligned}
E_t[W_{t+1}] &= W_t + (W_t - x_{t,f})y_t + [1 - \theta_t]x_{t,f}(f_t^B + y_t^* - s_t^A) + \theta_t x_{t,f}(E_t[s_{t+1}^B] + y_t^* - s_t^A), \\
&\quad \text{if } f_t - s_t > y_t - y_t^* \quad \text{and} \tag{9} \\
E_t[W_{t+1}^*] &= W_t^* + (W_t^* - x_{t,f})y_t^* + [1 - \theta_t]x_{t,f}(f_t^A + y_t - s_t^B) + \theta_t x_{t,f}(E_t[s_{t+1}^A] + y_t - s_t^B), \\
&\quad \text{if } f_t - s_t < y_t - y_t^*. \tag{10}
\end{aligned}
$$

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. θ_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, $-E_t[(-\rho W_{t+1})]$, gives the following certainty-equivalent objective function for 9

$$
\max_{x_{t,f}}\{W_{t+t}\} = W_t(1 + y_t) + x_{t,f}(f_t^B - S_t^A + y_t^* - r_t) - \frac{\rho}{2}\theta_t x_{t,f}^2 \sigma_s^2 \tag{11}
$$

which, imposing market clearing, $x_{t,f} = D_t^{XC} - \Lambda$, gives the forward rate as [15]

$$
f_t^B = s_t^A + y_t - y_t^* + \theta_t \rho \sigma^2 D_t^{XC} - \Lambda, \tag{12}
$$

where D_t^{XC} captures shocks to swap demand, where $D_t^{*,XC} \equiv -D_t^{XC}$, and Λ captures frictions arising from liquidity and transaction costs.[16]

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

$$
\begin{aligned}
CIP_{i,t}^- &\equiv r_{i,t} - (r_{i,t}^* + f_t - s_t) \\
&\geq \theta_t \rho \sigma_s^2 D_t^{XC} - \Lambda \tag{13}
\end{aligned}
$$

---

[15]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 $s \equiv \log(S)$.

[16]$\Lambda_t = c[(y_t^{*,REPO} - y_t^*) - (y_t^{REPO} - y_t)] + [(f_t^B - s_t^A) - (f_t^A - s_t^B)]$, which gives frictions arising from wholesale funding costs (where y_t^{REPO} 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

and equivalently

$$
\begin{aligned}
CIP_{i,t}^+ &\equiv r_{i,t} - (r_{i,t}^* + f_t - s_t) \\
&\leq \theta_t \rho \sigma_s^2 D_t^{XC} = \Lambda,
\end{aligned}
\tag{14}
$$

which are the arbitrage bounds, given in section 3.1. $\square$

A.2   FI Arbitrage Portfolio Optimisation

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

$$
E_t R_{(t,t+1)}^P - \frac{1}{2} \sigma Var_t R_{(t,t+1)}^P
\tag{15}
$$

$$
R_{(t,t+1)}^P = \sum_{i=1}^{N} \omega_t^i R_{(t,t+1)}^i = \sum_{i=1}^{N} \omega_t^i [exp(\overline{p}_{t+1}^i - \overline{p}_t^i) - 1]
$$

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

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

which is affine in a set of macroeconomic factors

$$
\psi_{t+1} = \gamma' X_{t+1}
\tag{16}
$$

which follow the VAR process

$$
X_t = \mu + \Phi X_{t-1} + \varepsilon_t \qquad \varepsilon_t \sim N(0, \Psi)
\tag{17}
$$

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

$$
\overline{p_t^i} = -\overline{a}_i - \overline{b}_i' X_t,
\tag{18}
$$

its corresponding risk-free one-period rate as

$$
\overline{r_t^i} = a_i + b_i' X_t,
$$

and the continuously compounded yield y_t^i on a n-period bond in habitat i as $-p_t^i/n$. Arbitrageurs' portfolio holding return can be expressed as

$$
\begin{aligned}
R_{(t,t+1)}^P &= \sum_{i=1}^{N} \omega_t^i [exp(-\overline{a}_i - \overline{b}_i' X_{t+1} + \overline{a}_i + \overline{b}_i' X_t) - 1] \\
&= \sum_{i=1}^{N} \omega_t^i [exp(\overline{b}_i'(X_t - X_{t+1})) - 1],
\end{aligned}
\tag{19}
$$

where an arbitrageur chooses ω_t^i such that[17]

$$\max \; E_t[R_{(t,t+1)}^P] - \frac{1}{2}\sigma Var_t[R_{(t,t+1)}^P]$$

$$s.t. \; : \; \sum_{i=1}^{N} \omega_t^i = 1 \tag{20}$$

where for small time increments we can approximate the conditional variance, $Var_t[R_{(t,t+1)}^P]$, and the conditional expected mean return, $E_t[R_{(t,t+1)}^P]$, such that[18]

$$E_t[R_{(t,t+1)}^P] \approx \sum_{i=1}^{N} \omega_t^{(i)}[(-(\bar{b}_i' + \gamma')(\mu + \Phi X_t)$$

$$+ \frac{1}{2}(\bar{b}_i' + \gamma)\Psi(\bar{b}_i' + \gamma) + \bar{b}_i' X_t]) \tag{21}$$

$$Var_t[R_{(t,t+1)}^P] \approx d_t' \Psi d_t,$$

where

$$d = \sum_{i=1}^{N}(\omega_t^i(\bar{b}_i + \gamma))$$

represents a factor of exposure to macroeconomic risk.

The FOCs of the Lagrangean, L_t, corresponding with (21) are

$$\frac{\partial L_t}{\partial \omega_t^i} = -(\bar{b}_i' + \gamma')(\mu + \Phi X_t) + \frac{1}{2}(\bar{b}_i' + \gamma)\Psi(\bar{b}_i' + \gamma) + \bar{b}_i' X_t \tag{22}$$

$$-(\bar{b}_i' + \gamma')\Psi\sigma\sum_{i=1}^{N}[\omega_t^i(\bar{b}_i + \gamma)] - \chi_t = 0,$$

---

[17]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 ω_t^i.

[18]Hamilton and Wu (2012) Hamilton and Wu (2012) show that for $q_{n,t+1} \equiv \frac{P_{(i,t+1)} - P_{it}}{P_{it}} = \exp\left(\mu_i h + \sqrt{h}\epsilon_{i,t+1}\right) - 1$, $(\epsilon_{1,t+1}, ..., \epsilon_{N,t+1})' \sim N(0, \Omega)$, the continuous time representation of a discrete time process,

$$E_t\left(\sum_{i=1}^{N} z_{it} R_{(t,t+1)}^P\right) = \sum_{i=1}^{N} z_{it}[\mu_i h + \Omega_{ii}h/2 + o(h)]$$

$$Var_t\left(\sum_{i=1}^{N} z_{it}\right) = z_t'\Omega z_t h + o(h),$$

for $h = 1$ and $o(h) = 0$ leads to

$$\frac{P_{(i,t+1)}}{P_{it}} = \exp[\bar{b}_i'(X_{t+1} - X_t)]$$

$$\mu_n = \bar{b}_i'(c + \gamma X_t) - \bar{b}_i' X_t$$

$$\Omega_{ii} = \bar{b}_i'\Psi\bar{b}_i,$$

which implies (21).

where χ_t is the Lagrange multiplier of the constraints.

Expressing the FOCs in terms of excess holding returns then yields

$$\text{where} \quad R^i_{(t,t+1)} - \bar{r}_t = \bar{b}'_i \Sigma \Sigma' \lambda_t$$

$$R^i_{(t,t+1)} \equiv -\bar{b}'_i(\mu + \Phi X_t) + \frac{1}{2}(\bar{b}'_i + \gamma')\Psi(\bar{b}_i + \gamma)$$
$$-\frac{1}{2}\gamma'\Psi\gamma + \bar{b}'_i X_t$$

$$\bar{r}_t = \bar{a}_i + \bar{b}'_i X_t$$

$$\lambda_t \equiv \sigma \sum_{i=1}^{N}(\omega^i_t(\bar{b}_i + \gamma)) \tag{23}$$

Investors follow their preferred-habitat motifs over specific maturities in their demand as

$$\xi^i_t = \varphi(\bar{y}^i_t - \beta^i) \tag{24}$$

where ξ^i_t is the demand relative to the arbitrageurs' net wealth W_t, and β^i its intercept. In equilibrium the combined demand from arbitrageurs and investors then needs to equal the supply of bonds S^i_t

$$\omega^i_t + \xi^i_t = S^i_t \tag{25}$$

which combined with (23) gives the market price of risk as

$$\lambda_t = \sigma \sum_{i=1}^{N}(S^i_t - \xi^i_t)(\bar{b}_i + \gamma) \tag{26}$$

Using 24 in 26 and rearranging the FOCs in terms of bond yields, r^i_t, gives 4. □

A.3 Proof of Eq. (7)

Substituting 6 into 7 and assuming swap market equilibrium we get

$$\begin{aligned}
\hat{b} \equiv & \left[\frac{1}{T}\sum_{i=1}^{T}\mathbb{E}\mathbf{r}_{t+i} + CP(\boldsymbol{x}, \iota) \times VP(\gamma, \lambda(\sigma, \omega(S, \xi), \bar{b}, \gamma), \Sigma\Sigma')\right] \\
& - \left(\left[\frac{1}{T}\sum_{i=1}^{T}\mathbb{E}\mathbf{r}^*_{t+i} + CP(\boldsymbol{x}, \iota)^* \times VP(\gamma, \lambda(\sigma, \omega(S, \xi), \bar{b}, \gamma), \Sigma\Sigma')^*\right] + f_t - s_t\right) \\
& + \theta_t\rho\sigma_s^2(\sigma^2, \sigma^{2*})D_t^{XC}(y, y^*) + \Lambda(r, r^*, r_{REPO}, r^*_{REPO}, f^A, f^B). \tag{27}
\end{aligned}$$

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 intervall sizes. We execute the tests for all models and compare results for restricted and unrestricted samples. Results are given in table 13 below.

Table 5: Quand-Andrews Breakpoint Tests

Statistic	3M		1Y		2Y		5Y	
	Full	Restr.	Full	Restr.	Full	Restr.	Full	Restr.
Maximum LR F-statistic	0.0171	0.0009	0.0084	0.0257	0.0046	0	0.0099	0.0082
Maximum Wald F-statistic	0.0171	0.0009	0.0084	0.0257	0.0046	0	0.0099	0.0082
Exp LR F-statistic	0.4499	0.0043	0.2256	0.0883	0.016	0.0016	0.0464	0.0616
Exp Wald F-statistic	0.0882	0.0003	0.0175	0.0272	0.0034	0.0001	0.0054	0.0122
Ave LR F-statistic	0.3183	0.0007	0.1356	0.0239	0.0014	0.0001	0.0101	0.0131
Ave Wald F-statistic	0.3183	0.0007	0.1356	0.0239	0.0014	0.0001	0.0101	0.0131
Suggested Date	12/04/2015	09/07/2014	12/04/2015	2/18/2015	12/04/2015	1/28/2015	11/28/2015	1/16/2015

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.[19] 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 6: Bai-Perron Tests

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

---

[19]For 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 7: Granger Causality Tests: Full Sample

Dependent Variables	Independent Variables			
	DCIP3m	DCIP1Y	DCIP2Y	DCIP5Y
D(100*FF)	0.463	0.0361	0.3389	0.6238
D(100*(S-FWD))	0.4986	0	0.0321	0.1746
D(100*REPO)	0.2973	0.5019	0.7266	0.7174
D(100*LIQUIDITY)	0.9908	0.0097	0.6211	0.0279
D(EPU)	0.5131	0.139	0.1937	0.1355

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 8: Granger Causality Tests: Restricted Sample

Dependent Variables	Independent Variables			
	DCIP3m	DCIP1Y	DCIP2Y	DCIP5Y
D(100*FF)	0.7602	0.0584	0.6567	0.7264
D(100*(S-FWD))	0.1536	0	0.3051	0.2651
D(100*REPO)	0.9064	0.2699	0.7467	0.4402
D(100*LIQUIDITY)	0.7371	0.4523	0.9154	0.6216
D(EPU)	0.5867	0.314	0.2053	0.2122

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.

B.3 Additional Tables for Section 4.2.3

Table 9: CCBS Regressions including EPU and CDS

	3m	1y	2y	5y	3m	1y	2y	5y
Mean		Excl. Outliers				Incl. Outliers		
GARCH	-6.676 ***	-0.018	-0.001	-0.008	0.001	0.023	0.001	-0.007
C	-1.643 ***	-0.026	0.007	-0.011	-0.015 *	-0.017	0.017	0.003
FF	0.078 ***	0.040	-0.083 ***	-0.097 ***	0.047 *	-0.031	-0.085 ***	-0.052 **
FWD	0.007 ***	-10.156 ***	-4.768 ***	-1.456 ***	0.002 ***	-7.310 ***	-4.524 ***	-1.490 ***
REPO	-0.005	-0.020	-0.081 ***	-0.078 ***	-9.411 ***	0.002	-0.039 ***	-0.037 ***
LIQUIDITY	2.925	3.853	-0.902 **	1.002 ***	0.001	4.346 *	-0.829 **	1.144 ***
CIP_{t-1}	0.682	-0.069 *	0.021	0.004	0.051 **	-0.068 **	0.028	0.006
CDSUS				-0.074 ***				-0.051 ***
CDSEUR				-0.006				-0.009 ***
Variance								
C(8)	-0.229 ***	-0.275 ***	-0.489 ***	-0.454 ***	-0.221 ***	-0.087 ***	-0.430 ***	-0.454 ***
ARCH	-0.003	0.388 ***	0.059	0.200 **	0.117 ***	0.221 ***	0.155 ***	0.200
Leverage	0.100 ***	0.134 *	0.192 ***	0.206 ***	0.032	-0.059	0.209 ***	0.206 ***
GARCH	0.064 *	0.102	0.452 ***	0.441 ***	0.563 ***	0.357 ***	0.542 ***	0.441 ***
VIX	-0.002	0.065	0.071	-0.039	-0.047	-0.020	0.113 ***	-0.039
FXV	0.002	-0.104	0.400 ***	0.359 **	0.142	-0.079	0.430 ***	0.359 ***
CPRISK	0.390	17.998 *	-12.415	-9.011	9.636 **	11.013 **	12.035	-9.011 ***
MPSI	0.001	-0.002	0.013	-0.011	0.041 ***	-0.013	-0.002	-0.011 *
EPU	0.000	-0.006 ***	-0.013 ***	-0.012 ***	-0.015 ***	-0.011 ***	-0.016 ***	-0.012 ***
t-DoF	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
R2	0.186	0.028	0.070	0.077	0.017	0.022	0.076	0.065
SER	0.894	0.976	0.730	0.752	1.207	1.287	0.820	1.001
BIC	2.425	2.676	1.995	2.177	2.617	2.884	2.066	2.359
DW	2.128	2.267	2.018	1.955	2.001	2.188	1.941	2.023

The table gives estimation output for specifications adding Economic Policy Uncertainty (EPU) in first differences to variances and 5y bank Credit Default Swap indices for US and European to the 5y basis. Dependent variables are 3m-5y CCBS rates. Estimation of all models via maximum likelihood assuming t-distributed errors 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%.

Table 10: CCBS Regressions Accounting for Timing of Exchange Trading Hours

	3m	1y	2y	5y	3m	1y	2y	5y
Mean		Excl. Outliers				Incl. Outliers		
GARCH	0.012	-0.397 **	-1.223 *	-0.081 *	0.004	-0.049	0.015	-0.008
C	-0.010	-0.038	-0.761 *	-0.051	-0.023	0.006	0.013	-0.002
FF^{sync}	0.023	-0.019	-0.149 ***	-0.123 ***	0.006	-0.002	-0.072 ***	-0.087 ***
FWD	-0.001	-18.983 ***	0.225	0.020	0.000	-13.187 ***	-0.530	-0.116
$REPO_{t-1}$	0.013	-0.025	-0.049 ***	-0.049 ***	0.005	-0.012	-0.004	-0.021 *
$LIQUIDITY_{t-1}$	-3.516	3.199	-0.872 **	1.153 ***	-8.752 ***	5.760 **	-0.635	1.144 ***
CIP_{t-2}	0.060 **	-0.009	-0.103 ***	0.023	0.054 **	-0.050	-0.047 **	0.021
Variance								
C(8)	-0.380 ***	-0.275 ***	-0.606 ***	-0.459 ***	-0.340 ***	-0.142	-0.969 ***	-0.554 ***
ARCH	0.115 *	0.388 ***	-0.063	0.275 ***	0.153 ***	0.435 ***	0.345 ***	0.377 ***
Leverage	0.039	0.134 *	-0.036	0.241 ***	-0.030	0.061	-0.030	0.190 ***
GARCH	0.275 **	0.102	-0.054	0.381 ***	0.093	-0.463 ***	-0.430 ***	-0.073
VIX	-0.237 ***	0.065	-0.030	-0.179 ***	-0.210 ***	0.012	-0.133 ***	-0.172 ***
FXV_{t-1}	-0.316 **	-0.104	0.197 *	0.233 *	-0.330 **	0.272 **	0.181 *	0.073
$CPRISK^{sync}$	-12.260 *	17.998 *	2.405	-11.589 *	-16.524 ***	5.351 *	-0.341	4.570
$MPSI_{t-1}$	0.046 ***	-0.002	0.001	-0.009	0.050 ***	-0.003	0.024 ***	-0.014
t-DoF	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
R2	0.005	0.091	0.081	0.023	0.008	0.048	0.025	0.022
SER	0.989	0.944	0.729	0.773	1.213	1.270	0.846	1.023
BIC	2.488	2.632	2.100	2.237	2.646	2.832	2.200	2.431
DW	1.946	2.232	2.038	1.930	1.942	2.217	1.866	2.013

The table gives results, correcting for delayed pricing of some of the underlying variables through time-zone differences between exchanges considered. Dependent variables are first lags of 3m-5y CCBS rates. FF^{sync} and $CPRISK^{sync}$ gives lags only the European part in respective variables. Estimation of all models via maximum likelihood assuming t-distributed errors 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%.

C   Measuring Policy Attention using Monetary Policy Search Indices (MPSI)

The Monetary Policy Search Index, MPSI, (Wohlfarth (2018b)) uses an index based on a number of search queries related to one particular central bank investigated. The index is constructed following the approach of Da et al. (2015) in that the search topics "European Central Bank" and "Federal Reserve System" are entered into the Google Trends user interface, which returns a list of related top searches, which will then enter each index, weighted by the impact value assigned by Google. Search terms that are ambiguous or unrelated will be excluded. It is crucial to stress at this stage that weights are not constructed through data-mining approaches such as using uninformed correlation measures, but instead are based on Google's measure of *related searches*, which gives correlations based on search terms the same users also entered and hence avoids spurious relationships.

Table 11: MPSI Indices – Search Words

Index	Search Words	weight
MPSI	European Central Bank	100
	ECB	55
	ECB rate	40
	EZB	25
	BCE	15
	Banco Central Europeo	5
	Banca Centrale Europea	5
	Europaeische Zentralbank	5
	Banque Centrale Europeenne	5
MPSI*		
	Federal Reserve	100
	Fed	65
	Federal Reserve System	60
	Fed interest	5
	Fed rate	5
	Federal Reserve Bank	5
	The Fed	5

The search words are selected by querying the search topics "European Central Bank" and "Federal Reserve System" with the Google Trends UI, where the search is limited to News Search only. Google reports a number of statistics with each search term queried. We use "related queries" from which we select the most popular search queries. The given metric for those related queries is then used as a weight in our indices. These metrics are described in the Google Trends UI as "Scoring is on a relative scale where a value of 100 is the most commonly searched query, 50 is a query searched half as often, and a value of 0 is a query searched for less than 1% as often as the most popular query."
We follow the same approach in the construction of our control indices.

The search indices for ECB and Fed related searches are plotted in figure 2. The vertical lines represent identified events, which are given in table 22 below. We can observe that the indices that the indices are clearly heteroskedastic and can identify several volatility spikes and clusters that coincide with policy events. The most significant events seem to be relating to the launch and extension of asset purchases for the ECB and interest rate hikes for the Fed, which is in line with the patterns we observed for the fixed income series. Identifying certain relevant events using our

indices is not a comprehensive exercise, which would compromise one of the reasons for using such measures, but provides evidence that the MPSI can replicate policy events and do not just follow noise.

Figure 1: Google Search Indices and Identified Events
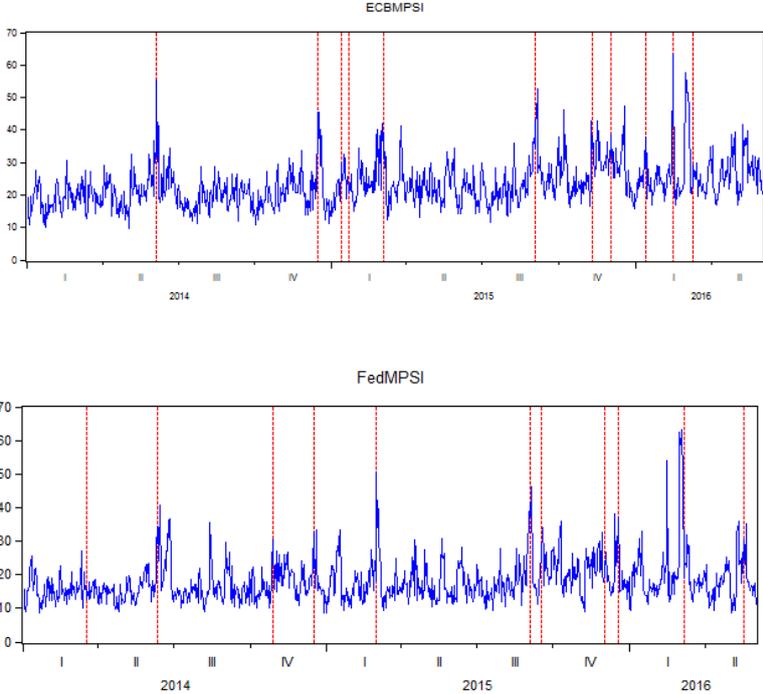
Notes: Vertical lines represent individual identified events. Vertical axis gives a search volume index value based on normalised index values obtained through Google Trends for individual search words (see appendix A.3 for details). Data source: Google Trends (www.google.com/trends)

Table 12: Identified ECB Events

Date	Event
05/06/2014	GC Meeting: Deposit rate from 0% to -0.1%; Refi rate from 0.25% to 0.15%; 4yr TLTRO, QE hint
16/12/2014	Bundesbank's Weidmann raises concern over QE
14/01/2015	ECJ Advocate General Approves of OMT
05/03/2015	GC meeting: Announcement to start purchases, as markets raise doubts on ECB's ability to conduct purchases; ELA extension (Greece)
09/03/2015	Benoit Coere confirms EUR3.2bn in purchases (as targeted)
03/09/2015	GC meeting: Hint towards further asset purchases
11/11/2015	Rumors ECB might engage in municipal bond purchases
03/14/2015	12/2015 GCM minutes released
21/01/2016	GC meeting: Draghi hints further asset purchases
15/02/2016	Dovish Draghi Speech at EP
10/03/2016	GC meeting: Deposit rate cut to -0.4; QE extension to EUR80bn/m, incl. corporate bonds

Table 13: Identified Fed Events

Date	Event
14/06/2014	Stanley Fisher appointed FOMC vice chair
29/10/2014	QE ended
17/12/2015	FOMC "paitent to raise rates"
02/03/2015	Appointment of Patrick Harker to succeed Charles Plosser at Phil. Fed
04/09/2015	Disappointing jobs report
17/09/2015	Dovish FOMC meeting
02/12/2015	Yellen hints rate hike
18/12/2015	First rate hike
07/03/2016	Comments from Fed's Brainard and Fisher
18/05/2016	FOMC minutes