A century of arbitrage and disaster risk pricing in the foreign exchange market*

Giancarlo Corsetti
University of Cambridge and CEPR

Emile A. Marin
University of Cambridge

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Abstract

A long-standing puzzle in international finance is that a positive interest rate differential systematically forecasts an exchange rate appreciation—the Uncovered Interest Parity (UIP) puzzle. Hence, a carry trade portfolio long in high yield currency bonds funded by borrowing in low yield currencies can be expected to yield positive profits. Following the Great Financial Crisis, however, the sign of the puzzle has changed—positive differentials forecast excessive depreciation—and carry trade has withered after the large losses suffered by investors in 2007-2008. In this paper, we use a century-long time series for the GBP/USD exchange rate to show that a sign switch is neither new, nor, arguably, a new puzzle. First, it is not new in the data—by virtue of a long sample featuring infrequent, non-overlapping currency crashes, we document that switches systematically occur in crises such as the Great Depression in the 1930s and the exchange rate turmoil of the 1990s. However, UIP deviations, sharp in either direction for short- to medium-horizon portfolios, remain small to almost negligible for long-horizon investment portfolios. Second, we argue that our century-long evidence is consistent with models featuring a time-varying probability of disasters or 'Peso events,' specified so to account for the difference in UIP deviations in crisis and normal times, as well as for a decreasing term structure of carry trade returns that on average characterize the data.

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Keywords: Uncovered Interest Parity, Peso Problem, Great Depression, Currency Crises, Carry Trade, Fama Puzzle

*Giancarlo Corsetti: gc422@cam.ac.uk; Emile Marin: eam65@cam.ac.uk. We thank Simon Lloyd for useful discussions. We thank the Bank for International Settlement and the Federal Reserve Bank of New York for hospitality when working on this paper. We acknowledge support by the Cambridge INET institute and the Keynes Fund at Cambridge University.

1 Introduction

The Uncovered Interest Parity (UIP) hypothesis is one of the defining building blocks of international finance, and its failure to hold in the data has created a long standing puzzle. In its simplest formulation, the UIP hypothesis states that nominal interest rate differentials across currencies should forecast expected exchange rate movements: investing in a currency that is expected to lose value over, say, the next three months should require higher three month nominal interest rates. However, running the Fama (1984) regression (changes in exchange rates regressed on interest differentials), researchers and practitioners have long found that the "Fama coefficient" (the coefficient on nominal rate differentials) is generally not close to one as is predicted by the UIP. Rather, based on analyses of samples including mostly advanced countries in a period preceding the global financial crisis, the coefficient is non-positive and close to -1, therefore, positive differentials forecast appreciation. Recently, it has been noted that this well-documented result breaks down during the Global Financial Crisis. After 2007, the coefficient turns positive and larger than 1, motivating Bussière et al. (2018) to claim that we now have a 'new Fama puzzle'. We are led to ask: is the new Fama puzzle really new, or rather, has the post-2007 evidence called attention to a pattern that, while present in the historical data, was not noted before? Most importantly, is this switch consistent with leading explanations of the puzzle in the literature as a unified analytical framework?

In this paper we address these questions, first, by presenting historical data on the USD-GBP currency pair, to obtain a long time series with desirable properties (e.g., relatively free capital mobility between the countries issuing the two currencies) delivering novel empirical evidence; and, second, by drawing on the literature on the "Peso problem", to explain this evidence and gain insight on the role disaster risk in driving return from arbitrage in the international financial markets.

Our main contributions are as follows. On empirical grounds, we show that the reversals in the UIP anomaly are recurrent around periods of severe crises. In our time series, these periods include not only the 1930s and the post-2007 years, but also the early to mid-1990s, when Europe was shaken by a systemic currency crisis that led to the withdrawal of the sterling pound from the European Monetary System. Furthermore, thanks to the length of our time series, we document the dynamics of exchange rates and excess currency returns in anticipation, during, and in the aftermath of Peso events. We stress the importance of a long empirical sample in validating any model based on rare events. The presence of distinct, non-overlapping peso events, decades apart from each other, provides us with the statistical power to test the UIP condition in sub samples, and enable us to compare returns on short and long-maturity carry trade (i.e., the term-structure of carry trade) across these events.

Based on this evidence, we argue that the 'UIP puzzle' should be articulated along three key empirical dimensions, to account for the fact that the Fama coefficient varies systematically both across normal and crisis periods, and depending on the investment horizons employed in the analysis. Synthetically, the Fama coefficient is:

1. significantly below unity and typically non-positive for investment horizons up to 5-7 years,

as stressed by the textbook treatment of the UIP puzzle, in normal times;

2. positive, and significantly above unity during crises;

3. on average, closer to unity for long than for short and medium-term investment horizons, across both normal and crisis times.

The above implies that carry trade profits are, on average, positive for short and medium investment horizons, negative during crises, and small (in annualised terms) for long investment horizons. Together, the first and third feature of the data further imply that, in normal times, the terms structure of carry trade return is on average downward sloping: annualised returns to short maturity portfolio are higher than the corresponding returns to long maturity portfolios.[1] Throughout the analysis, we define "normal times" as periods in which business cycle movements are neither associated with financial crises, nor give rise to abnormally large and persistent downturns.

On theoretical grounds, we show that this evidence lends empirical support to models drawing on the Peso problem and disaster risk literature, and featuring a time-varying probability of extreme events. We derive conditions on the process driving this probability such that the model is able predict systematic sign reversals of the Fama coefficient during disaster, as well as the average term structure of carry trade profits. We stress that, to inform our theoretical framework, we also use information on the realised exchange rate dynamics during and after Peso events—in this respect, we deviate from existing studies of disaster risk, that typically take an ex-ante perspective focusing on the implications for exchange rate determination *before* disasters occur.

Our analysis has at least one relevant implication for policy. It has been argued that the sign reversal in the UIP regression after 2007 can be attributed to unconventional monetary policy, see e.g Stavrakeva and Tang (2018). The crises in our sample, in the 1930s, the 1990s and the recent Global Financial Crisis, are all characterized by a sign reversal, but also by quite different stabilization policy regimes. We take this as evidence that reversals cannot be systematically associated to unconventional monetary policy—nothing close to QE was implemented in the 1930s.

Our work relates to the literature analyzing disaster risk in a historical perspective, as in Barro (2006). We build on a classical strand of literature on 'Peso' events, as studied in Burnside et al. (2011) and later surveyed in Engel (2014), but allow for time-varying disaster probabilities as in Gabaix (2012) and Gourio (2012). The disaster risk literature highlights that the possibility of rare events gives rise to risk premia, thus the UIP anomaly holds even in samples which feature disaster events. Time variation in the UIP coefficient in relation to the terms structure of interest rates has been recently studied by Lloyd and Marin (2019), while the term structure of carry trade has been brought to focus in the literature by Lustig et al.

[1] It is worth noting that, even if the Fama coefficient is close to one, ruling out pure Carry Trade excess returns, excess returns on arbitrage portfolios may still be high, if driven by factors uncorrelated with the interest rate differential.

(2019). An instance of an early study detecting systematic changes in the Fama coefficient is Flood and Rose (2002).

In section 2 we detail the data we use and highlight our main empirical results. In section 3 we present a simple framework with time-varying disaster risk which captures our key stylized facts. Section 4 concludes.

2 The new Fama puzzle is hundred year old

2.1 Data and methodology.

We use monthly data from the Global Financial Database on U.S. and U.K. 3 month and 10 year government bond yields, as well as the end of month USD/GBP nominal exchange rate for the period 1920 January to 2016 December. While our sample is constrained by historical data availability, we should stress an advantage of focusing on the country pair U.S. and U.K., that is, capital flows between the two remained relatively free during the 1930s.

We estimate the following regression by ordinary least squares:

$$e_{t+\kappa} - e_t = \beta_{0,\kappa} + \beta_{1,\kappa}(i_{t,\kappa} - i^{\$}_{t,\kappa}) \tag{1}$$

where $e_{t+\kappa} - e_t$ is the log realised $\kappa-$ month exchange rate change (a positive change corresponds to a GBP depreciation) and $(i_{t,\kappa} - i^{\$}_{t,\kappa})$ is the difference between the log $\kappa-$ month UK yield and the corresponding US bond yield. The coefficient $\beta_{1,\kappa}$ in the above regression is customarily referred to as the Fama coefficient. Since we are interested in time variation in this coefficient, we estimate the above regression using rolling windows of 5 years for κ =3 month regressions and 30 years for analogous κ =10 year regressions:[2] A rolling window estimation allows us to exploit the length of our time-series and independently estimate the coefficient β_1 in samples which do not contain crises and samples which do. Additionally, we borrow from Lloyd and Marin (2019) and overlay our results against an indicator variable that takes a value of 1 following a U.S. yield curve inversion, and maintains this value until the end of the corresponding NBER recession. This allows us to study UIP dynamics during recessions from the moment they are priced into domestic bonds. In all the figures below, for each recession, we will mark this time span with a shaded area.

Arbitrage in the 1930's. The 1930s are of particular interest to us because UIP dynamics (sign and magnitude of deviations) as well as macro conditions and market sentiments, are somewhat comparable with the period following the financial crisis in 2008. However, the UIP condition can only be expected to hold if capital is allowed to flow freely across countries. For this reason, we dig into the history of US-UK capital flows over that period and investigate whether the conditions for the UIP to hold are verified. Drawing on the literature, see, e.g.,

[2] The results are very similar when considering variations in the size of the rolling windows. We ensure that the length of the window exceeds the maturity of the bond to account for the possibility that bonds are held to maturity.

Ghosh and Qureshi (2016) and Feinstein et al. (2008), one can roughly distinguish two periods. The first runs through the 1920s, following the Dawes Loan (1924) financing German reconstruction after the war.[3] At the time, American banks entered a period of large international lending and capital ran from the US to overseas. Consistently, during the second half of the 1920's, the standard UIP anomaly is in play: a long position in the low yield currency would have earned slightly negative returns.

The second period coincides with the decade following the 1929 US stock market crash. This period is marked by a reversal of capital flows, with large inflows into the US. Importantly, the US government resisted the temptation to impose capital controls. By way of example, as late as 1937, Henry Morgenthau, the US Secretary of Treasury, wrote: "I am opposed to exchange control, except as a last resort. Frankly, I disapprove of exchange control."[4] The US did use measures that could be classified as "macroprudential policies". As an important instance, the US doubled the reserve requirements for banks to offset inflationary pressures in 1936-37 but this did not stop the inflow, see the discussion in Ghosh and Qureshi (2016) concerning capital flows in the pre-Bretton Woods period.[5]

2.2 Evidence

Results from our rolling regressions are shown in Figure 1. The upper panel, Figure 1a, plots the Fama coefficient for short horizon investment; the lower panel, Figure 1b, for long horizon investment.[6] Together, these panels provide evidence supporting our three-dimensional redefinition of the UIP puzzle.

Our first dimension states that the conventional view of the UIP anomaly, a Fama coefficient that is negative or close to zero, applies only for a short horizon investment and outside of crisis periods. This result, which characterizes a large part of our sample, is apparent in Figure 1a. We stress that the textbook UIP puzzle characterize both periods of expansion and downturns not associated with crises (see the corresponding shaded areas in the figure). Yet, the figure also vividly documents the reversal of the UIP anomaly during periods of great financial and economic stress, our second dimension. In particular, the reversal is a robust empirical finding dating back to the 1930s.

In Figure 1, the post-2007 currency market pattern mirrors that of the 1930s. In both periods, the reversal of the UIP occurs during a crisis with systemic global dimensions, where most advanced economies find themselves in a liquidity trap associated with financial and macroeconomic stress. It should be stressed that the reversal is very similar notwithstanding the significant differences in the policy response to the crisis. In the recent crisis, fiscal policy was,

[3] This was a publicly endorsed but privately resourced loan from the US to Germany for war reconstructions.

[4] Source: Bloomfield (1950).

[5] The Bretton Woods period refers to a fixed (fluctuations up to 1%) exchange rate regime negiotiated amongst the United States, Canada, Western European countries, Australia, and Japan in 1944, which was officially in place until 1971.

[6] In Figure 1 and 2 we report results for our entire sample (1920-2016), including the decades after World Word II when, under the early Bretton Woods agreements, capital controls prevented cross border arbitrage. We abstract from analysing the Bretton Woods period in our discussion.

at least initially, relaxed and central banks engaged in a number of non-conventional policies that sustained asset prices and kept liquidity provision abundant. In the 1930s, the fiscal and monetary response was quite conservative (see e.g. Eichengreen and Temin (1997) for a discussion). Based on the above evidence, it is hard to systematically attribute UIP reversals to unconventional monetary policy, or other recent policy and financial developments, which can only go so far in explaining the phenomenon. [7]

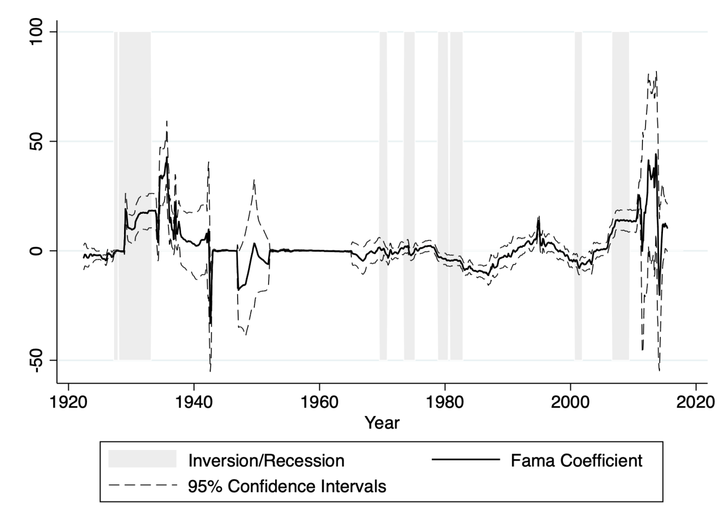
While the similarity of currency market patterns in the 1930s and the GFC is apparent, the coefficient plot in Figure 1 also suggests that the UIP regression yields a positive UIP coefficient in the 90s, around another crisis. At the time, the currency turmoil in the European Monetary System marked the exit of the sterling pound from the exchange rate arrangement of European countries (see Buiter et al. (1998)). This is further evidence that a *reversal* of the UIP puzzle seems to be systematically associated with periods of crisis, and not to different (monetary) policy regimes.[8] Monetary policy may nonetheless matter for the size of the Fama coefficient. Note that during crisis periods this coefficient reflects, inversely, the variance of the interest rate differential. The coefficient is very large in the 1930s and in the post 2007 period, when the yields on US and UK short bonds (3 month) converge and remain fairly stable as a result of monetary policy. It is smaller in the 1990s, when interest rates did not converge and their differential was much more variable. Other than these the three crisis periods (excluding the Bretton Woods era of fixed rates and controls), the conventional UIP puzzle, namely the excess appreciation of high yield currencies, is very robust.

Coming to the third dimension of our reformulation of the UIP puzzle, our historical evidence also squares a result emphasized by Chinn and Meredith (2005) for a sample of countries in recent decades. Violation of the UIP hypothesis, large and significant when assessed at investment horizons of business cycle frequencies (Figure 1a), actually becomes much smaller when the investment horizons is longer (greater than 5-7 years). Figure 1b plots the coefficient on yield differentials when we run our rolling-window regression model with 10 year yields. The figure shows that, irrespective of crisis periods (and excluding the period of capital controls under Bretton Woods), the coefficient of the yield differential is relatively stable over the sample, and much closer to unity compared to Figure 1a. This is also evidence that UIP reversals are relatively short-lived. These results are in line with the existing literature arguing that UIP holds 'better' over long-horizon, see Figure 1, Chinn and Meredith (2005) and Engel (2016) among others.

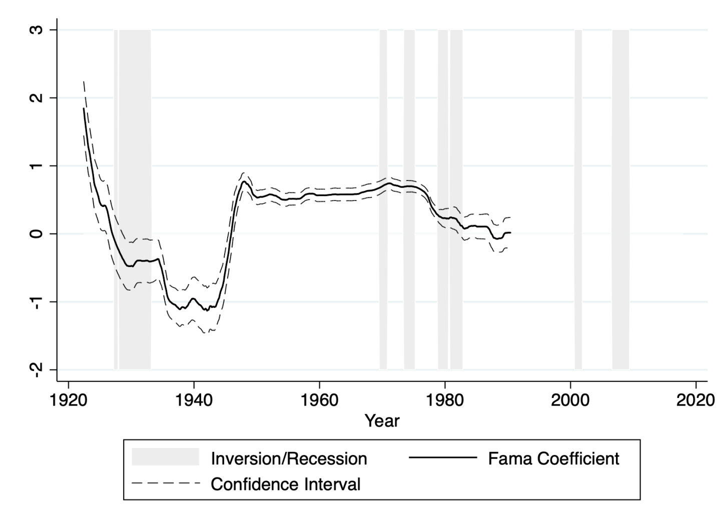
In our sample, the three crisis periods—the 1930s, the mid 1990s and the post-2008 period—coincide with a sharp fall in carry trade returns, corresponding to *currency crashes.* Figure 2 presents the log five year *non-annualized* carry trade profits for two portfolios: one constructed with 3-month bonds held to maturity and a second one constructed with 10-year bonds. Both

[7]In the same vein, one should note that, in general, monetary policy does not seem to have strong effects on carry trade profits in our sample as is the case of the strong (conventional) monetary policy tightening in the 70s and 80s.

[8]Related to our observation, Flood and Rose (2002), using daily data for 23 countries, noted that during the crisis-strewn 1990s, the UIP condition was better supported in the data: "in the sense that the slope coefficient from a regression of exchange rate changes on interest differentials yields a positive coefficient."



(a) 3-month interest rates, 5 year rolling window.



(b) 10-year interest rates, 30 year rolling window.

Figure 1: Source: Global Financial Database. Black line refers to rolling average of regression coefficient β_1 on $e_{t+1} - e_t = \beta_0 + \beta_1(i_{t,1} - i_t^{\$})$, eq. 1. Dotted lines refer to 95% confidence intervals. The shaded black regions reflect periods which commence with a U.S. yield curve inversion and last until end of the corresponding NBER recession date.

consist of long positions in the high yield currency, are funded by shorting the low yield currency, and are rebalanced every 3 months. Short maturity carry trade profits are, as expected, mostly positive outside of crises but turn negative during periods of crises when the Fama coefficient exceeds one. Carry trade profits using long maturity bonds (10 years) held to maturity follow a similar pattern. Note that at the time of a currency crash, relative to the returns on the short-run portfolios, the ex-post returns on long-run portfolios are larger in absolute (non-annualized) terms, but smaller once returns are annualised. These findings are consistent with the estimates of regression (1).[9] In the Appendix, we supplement our findings concerning annualised carry trade returns using post 1980 data, combining 1, 5 and 10 year bonds held to maturity.[10]

There are a number of additional factors which may weigh on the returns to long-maturity carry trade more than on short-maturity carry trade. First, especially in periods of high and volatile inflation, investors holding long- maturity bonds must be compensated for expected inflation differentials (see e.g. Piazzesi and Schneider (2007)), contributing to both to the size and volatility of the returns. By way of example, inflation is 24% in the UK in 1975, while just over 9% in the U.S and this is reflected in large carry trade profits for that period. Second, as shown in Lloyd and Marin (2019) using data from Du et al. (2018), there is evidence that long maturity carry trade returns disproportionately reflect differences in liquidity/convenience yields.[11] In the next section, we abstract from these considerations, to highlight the scope for time-varying disaster risk to rationalise the three dimensions of the UIP anomaly we have outlined above.

3 A Model with Disaster Risk

In light of our evidence, we now reconsider a leading explanation of the UIP puzzle which builds on the idea of disaster risk (see Barro (2006), Gabaix (2012) and Gourio (2012)), closely related to the international finance literature on the so-called “Peso problem” (see Burnside et al. (2011)). In this section, we first show that, in a simple framework of rare disasters, a switch in the sign of the UIP coefficient arises naturally during a crisis (delivering the first two dimensions of the UIP anomaly). Second, we derive simple conditions under which a time-varying probability of disaster generates a decreasing term-structure of carry trade returns consistent with our empirical findings.

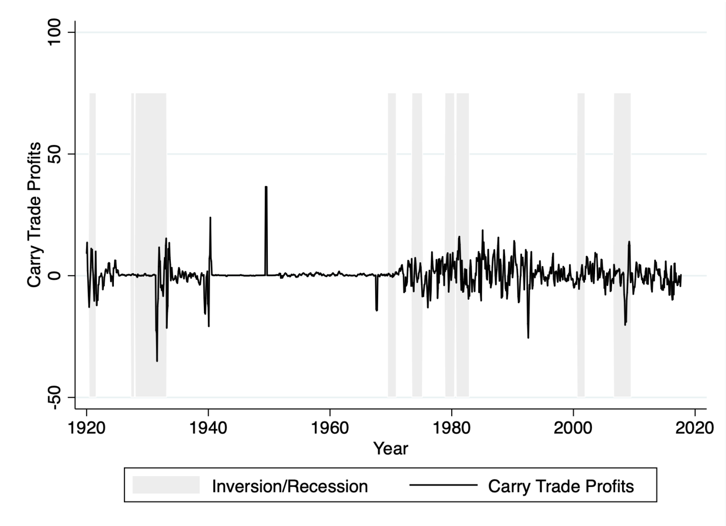
3.1 Pricing low-probability disasters

In the tradition of international finance, a ‘Peso event’ can be defined as a low probability event in which a currency that trades at premium (i.e., it is associated with a high nominal risk-free interest rate) may suffer a large devaluation. An important later refinement of the

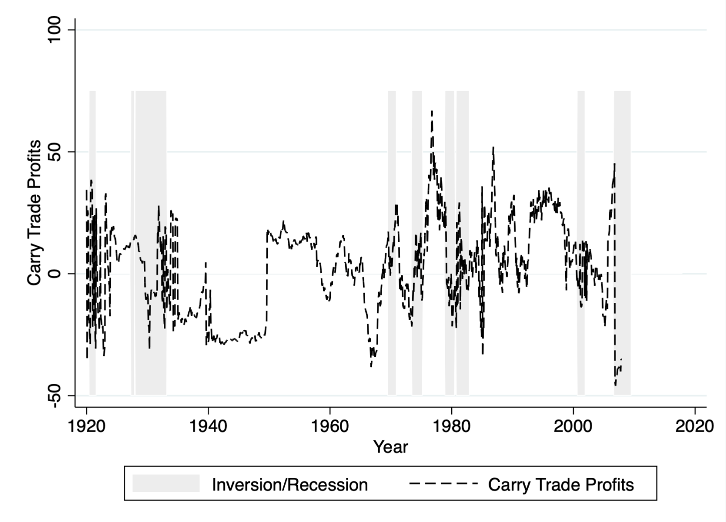
[9] Since the Fama regression in logs is scale invariant up to the constant, a coefficient approaching 1 for the 10 year maturity reflects lower annualised returns to long maturity carry trade.

[10] The data in the appendix has the key advantage of referring to zero coupon bonds, see Lloyd and Marin (2019). Results are clearly comparable.

[11] See also Engel and Wu (2018).



(a) 3-month interest rates



(b) 10-year interest rates

Figure 2: Source: Global Financial Database. Log, annualised, carry trade profits, unannualised, for a 3-month portfolio (a) and a 10-year portfolio (b), with three month rebalancing.

theory, stressed e.g. by Burnside et al. (2011), adds that a Peso event is characterized by a large increase in the marginal utility of the investors, as is the case in an economic “disaster” causing a fall in wealth and consumption. Under these conditions, if an investor has engaged in carry trade, i.e. borrowed in the low yield currency to invest in a high yield currency speculating on an expected appreciation, during a Peso event she/he will suffer a financial loss that is not only large, but also painful in terms of utility. While in most periods such an event may not occur, investors are wary of the possibility—hence they demand a premium which explains why the exchange rate in a country with high interest rate is still expected to appreciate.

The Peso problem is typically formalised as follows. Denote by M_{t+1}/M_t the one-period (month) stochastic discount factor (SDF) of an investor with access to both UK and US bonds. Let $R^{£}_{t,1}$ and $R^{\$}_{t,1}$ denote the nominal one period interest rates on UK and US bonds respectively, where, on average, $R^{£}_{t,1} > R^{\$}_{t,1}$. Let $\mathcal{E}_{t+1}/\mathcal{E}_t$ denote the nominal exchange rate change, with a value greater than one corresponding to a GBP depreciation. In an equilibrium with free capital mobility, the UK-based investor must be indifferent between saving in either bond and therefore the return to a carry trade portfolio long in U.K bonds and short in U.S bonds must satisfy the following:

$$\mathbb{E}_t\left[\frac{M_{t+1}}{M_t}\left(R^{£}_{t,1} - \frac{\mathcal{E}_{t+1}}{\mathcal{E}_t}R^{\$}_{t,1}\right)\right] = 0. \tag{2}$$

Now, assume that all future states of the world can be split into two sets, a Peso-event (PE) set and a no-Peso-event set (NPE), $s \in \{PE,\ NPE\}$. In addition, denote with $x^s = R^{£}_{t,1} - \frac{\mathcal{E}^s_{t+1}}{\mathcal{E}^s_t}R^{\$}_{t,1}$ the cash flow from the arbitrage position in the two currencies, in each state, and π_{t+1} is the probability of a Peso event at time $t+1$. The expected discounted returns at time t, of a carry trade portfolio paying off at $t+1$, can then re-written as follows:

$$(1-\pi_{t+1})\mathbb{E}^{NPE}_t\left[\frac{M^{NPE}_{t+1}}{M_t}x^{NPE}_{t+1}\right] + \pi_{t+1}\mathbb{E}^{PE}_t\left[\frac{M^{PE}_{t+1}}{M_t}x^{PE}_{t+1}\right] = 0, \tag{3}$$

where $\mathbb{E}^{NPE}_t[.], \mathbb{E}^{PE}_t[.]$ denote expectations formed at time t conditional on $s_{t+1} = \{NPE, PE\}$ respectively. Rearranging, we can derive the equilibrium excess return during a non-Peso event:

$$\mathbb{E}^{NPE}_t\left[\frac{M^{NPE}_{t+1}}{M_t}x^{NPE}_{t+1}\right] = -\hat{\pi}_{t+1}\ \mathbb{E}^{PE}_t\left[\frac{M^{PE}_{t+1}}{M_t}x^{PE}_{t+1}\right] \geq 0. \tag{4}$$

where $\hat{\pi}_{t+1} = \frac{\pi_{t+1}}{1-\pi_{t+1}}$ is the odds-ratio for a Peso event (defined as the ratio of the probability of a Peso event occurring next period relative to its complementary probability.) An excess return outside of Peso events is required to compensate investors for the possibility of a large loss ($x^{PE}_{t+1} << 0$), which carries a high valuation ($M^{PE}_{t+1} >> 0$) in the case of a Peso event.[12] Note that, for a given excess return $\mathbb{E}^{NPE}_t\left[\frac{M^{NPE}_{t+1}}{M_t}x^{NPE}_{t+1}\right]$, the smaller the probability of a Peso event, the larger the implied expected discounted losses during a Peso event, according to (2). The literature has long debated how to decompose the valuation of losses during Peso events into variation in the SDF and pecuniary losses (i.e a large depreciation of the funding currency). Burnside et al. (2011) use options to discern that Peso events are predominantly driven by the former, consistent with the notion of a steep decline in consumption a la Barro (2006).

In the consensus view in the literature, UIP deviations outside crises—the excess appreciation of the high yield currency in samples without Peso events—are at least in part attributable

[12] The excessive depreciation of the high yield currency during a Peso event is an equilibrium outcome in models with disasters risk see, e.g., in Farhi and Gabaix (2016) who consider both a global disaster risk and country-specific vulnerabilities

to such low probability, extreme events.[13] However, when a Peso event materializes in sample, the above relationship inverts:

$$\mathbb{E}_t^{PE}\left[\frac{M_{t+1}^{PE}}{M_t}x^{PE_{t+1}}\right] = -\frac{1}{\hat{\pi}_{t+1}}\ \mathbb{E}_t^{NPE}\left[\frac{M_{t+1}^{NPE}}{M_t}x_{t+1}^{NPE}\right] \leq 0. \tag{5}$$

Rolling our regressions through a peso event, we should expect to find positive UIP coefficients—as we do in Figure 1. A framework relying on peso events to interpret the UIP anomaly therefore provides a natural starting point for studying switches in the sign of the coefficient on interest differentials during periods of extreme economic and financial distress.

3.2 Time-varying probabilities of disasters and the terms structure of carry trade

Our long time series evidence suggests that excess returns to carry-trade vary significantly both over time and investment horizons, suggesting that the perception and pricing of disaster risk is not constant. Leading papers in the literature already incorporate time variation in disaster risk in the model, most notably Barro (2006), Gabaix (2012) and Gourio (2012), either as a changing probability of disasters, or a change in their magnitude. In what follows we will characterize conditions under which time variation in disaster risk can account for the three dimensions in our empirical redefinition of the puzzle, including switches in the sign of the Fama coefficient and the decreasing term-structure of carry trade. We do so in reference to a benchmark case in which, if the perceived probability of a disaster is constant, the term structure of carry trade returns is flat outside of Peso events.

With a simple extension, we incorporate time-varying disaster risk and carry trade portfolios of different maturities in the model from the previous section. Let $\mathbb{E}_t[(M_{t+\kappa}/M_t)\ x_{t+\kappa}]$ be the conditional expectation at time t of the valuation of returns in period $t+\kappa$ and let $\pi_{t+\kappa|t}$ be the conditional probability at time t of a Peso event occurring at $t+\kappa$. Consider two carry trade portfolios maturing at $t+\kappa$, which differ only in their maturity: a short-term ($j-$ maturity) portfolio that pays off $x_{t+\kappa}^{(j)}$ and a ($\kappa-$ maturity) portfolio that pays off $x_{t+\kappa}^{(\kappa)}$.[14] The no arbitrage pricing conditions for the short and long portfolio, respectively, can be expressed as follows,

$$\pi_{t+\kappa|t+\kappa-j}\mathbb{E}_{t+\kappa-j}^{PE}\left[\frac{M_{t+\kappa}}{M_{t+\kappa-j}}x_{t+\kappa}^{(j)}\right] + (1-\pi_{t+\kappa|t+\kappa-j})\mathbb{E}_{t+\kappa-j}^{NPE}\left[\frac{M_{t+\kappa}}{M_{t+\kappa-j}}x_{t+\kappa}^{(j)}\right] = 0$$

$$\pi_{t+\kappa|t}\mathbb{E}_t^{PE}\left[\frac{M_{t+\kappa}}{M_t}x_{t+\kappa}^{(\kappa)}\right] + (1-\pi_{t+\kappa|t})\mathbb{E}_t^{NPE}\left[\frac{M_{t+\kappa}}{M_t}x_{t+\kappa}^{(\kappa)}\right] = 0$$

[13] A recent contribution by Farhi et al. (2015) stresses that the pricing equation has explanatory power even if Peso events occur in sample.

[14] Lustig et al. (2019) present a different version of long-run UIP expressed in holding period returns. They show that the returns to a one period carry trade portfolio consisting of κ maturity bonds are also zero because bond premia and exchange rate premia offset one another.

Rearranging these equations in terms of excess returns in the non-Peso event state yields,

$$\mathbb{E}^{NPE}_{t+\kappa-j}\left[\frac{M_{t+\kappa}}{M_{t+\kappa-j}}x^{(j)}_{t+\kappa}\right] = -\hat{\pi}_{t+\kappa|t+\kappa-j}\ \mathbb{E}^{PE}_{t+\kappa-j}\left[\frac{M_{t+\kappa}}{M_{t+\kappa-j}}x^{(j)}_{t+\kappa}\right], \qquad (6)$$

$$\mathbb{E}^{NPE}_{t}\left[\frac{M_{t+\kappa}}{M_{t}}x^{(\kappa)}_{t+\kappa}\right] = -\hat{\pi}_{t+\kappa|t}\ \mathbb{E}^{PE}_{t}\left[\frac{M_{t+\kappa}}{M_{t}}x^{(\kappa)}_{t+\kappa}\right]$$

where $\hat{\pi}_{t+\kappa|t+\kappa-j}$ is the conditional odds ratio at any time $t+\kappa-j$ of being in a Peso event at $t+\kappa$.

Consider a benchmark case where investors value carry trade returns outside Peso event equally for $\kappa-$ and $j<\kappa$ maturity portfolios:

$$E_t\left[\frac{M^{NPE}_{t+\kappa}}{M_t}x^{NPE\ (\kappa)}_{t+\kappa}\right] = E_{t+\kappa-j}\left[\frac{M^{NPE}_{t+\kappa}}{M_{t+\kappa-j}}x^{NPE\ (j)}_{t+\kappa}\right], \text{ for all } j<\kappa \qquad (7)$$

This expression follows from (6) under the assumptions that: (i) the *ex-post valuation of losses* on carry trade portfolios are similar across maturities and (ii) the probability of disaster is i.i.d., such that $\pi_{t+\kappa|t+\kappa-j}$ is given by some constant p.[15] To take equation (6) to the data, we can further assume that (iii) SDF and portfolio returns are i.i.d. conditional on being in a Peso event and not being in a Peso event, possibly with different mean and variance across the two. Under this assumption, valuation and expected returns move proportionally.

By virtue of condition (i) we can isolate the time variation in the conditional probability of disasters as the main driver of carry trade returns (outside of Peso events). A candidate process for the probability of a disaster event is one resulting from the sum of a permanent and a transitory component:

$$\pi_t = \pi^{\mathbb{P}}_t + \pi^{\mathbb{T}}_t, \qquad (8)$$

such that, conditional on a positive transitory shock to disaster probability $\epsilon_{t+j}>0$,

$$\mathbb{E}_t[\pi^{\mathbb{P}}_{t+1}] = \pi^{\mathbb{P}}_t; \pi_{t+j} \geq \pi^{\mathbb{P}}_t \text{ and } \mathbb{E}_t[\pi_{t+\kappa}] = \pi^{\mathbb{P}}_t, \qquad (9)$$

for some $j<\kappa$.[16] Such a process has two key implications. First, $\lim_{\kappa\to\infty} E_t[\hat{\pi}_{t+\kappa}] = \hat{\pi}^{\mathbb{P}}_t$, which implies that carry trade returns on infinite maturity bonds, i.e evaluating (6) for $\kappa\to\infty$, reflect the permanent component of disaster risk only.[17] Second, taking the difference in the return on

[15] Condition (i) implies,

$$E_t\left[\frac{M^{PE}_{t+\kappa}}{M_t}x^{PE\ (\kappa)}_{t+\kappa}\right] \approx E_{t+\kappa-j}\left[\frac{M^{PE}_{t+\kappa}}{M_{t+\kappa-j}}x^{PE\ (j)}_{t+\kappa}\right], \text{ for all } j<\kappa$$

[16] The decomposition above, derived in Lloyd and Marin (2019), is useful since, as we show below, deviations from long run UIP correspond to differences in the permanent (long-run) exposure of currencies to disasters, extending the result in Lustig et al. (2019) who attribute long-run UIP deviations to permanent (Gaussian) innovations to the SDF.

[17] As in Alvarez and Jermann (2005) and Lustig et al. (2019), we use returns on 10-year bonds to approximate infinite maturity bonds.

the $\infty-$maturity portfolio and the $j-$maturity portfolio, shown below,

$$\mathbb{E}_{t+\kappa-j}\left[\frac{M_{t+\kappa}}{M_{t+\kappa-j}}x^{(j)}_{t+\kappa}|s_{t+\kappa}=NPE\right]=-\hat{\pi}_{t+\kappa|t+\kappa-j}\ \mathbb{E}_{t+\kappa-j}\left[\frac{M_{t+\kappa}}{M_{t+\kappa-j}}x^{(j)}_{t+\kappa}|s_{t+\kappa}=PE\right]$$

approximately yields the transitory component of the probability process,

$$\hat{\pi}_{t+\kappa|t+\kappa-j}-\hat{\pi}^{\mathbb{P}}_t=\hat{\pi}^{\mathbb{T}}_{t+\kappa|t+\kappa-j}$$

In periods when there are positive transitory innovations to disaster risk between t and $t+\kappa-j$ (as per (9)), the term-structure of carry trade is decreasing.[18] This may not be true in all periods but, as we highlight in our numerical example below, over long samples, because $\pi^{\mathbb{P}}_t$ is small and $\pi_t \geq 0$, the term-structure is decreasing on average. As Barro puts it, "disasters are not offset in a probabilistic sense by bonanzas" (see Barro (2006), p.26).

Our benchmark predicts that the valuation of carry trade returns on 10-year portfolios are smaller than those on short (3-month) portfolios.

$$\mathbb{E}^{NPE}_{t+\kappa-1}\left[\frac{M_{t+\kappa}}{M_{t+\kappa-1}}x^{(1)}_{t+\kappa}\right]>\mathbb{E}^{NPE}_{t}\left[\frac{M_{t+\kappa}}{M_{t}}x^{(\kappa)}_{t+\kappa}\right] \tag{10}$$

Qualitatively, this is in line with our evidence on the Fama coefficient estimated at difference horizons (Figure 1), and, under condition (iii) above, our evidence that annualised carry trade profits are smaller at long horizons (Figure 2). It is also consistent with the fact documented by Lustig et al. (2019), that holding period carry trade returns are decreasing. Quantitatively, relatively to the benchmark model, our evidence suggests that the losses of long-maturity carry trade in a Peso event are too small—implying that the return outside Peso events are also too small.

A caveat is in order however. In our framework we take interest rates as given and thus attribute variation in carry trade profits resulting from disaster risk exclusively to variations in exchange rates. However, disaster risk may be also priced in cross-country interest rate differentials. In this case, losses during Peso events for long maturity portfolios would be partly offset by bond term premia—a point discussed e.g. by Farhi and Gabaix (2016). This is a promising avenue to improve the match of the model with the data, that we explore in related research.

3.3 A numerical illustration

To illustrate how, under the probability process (9), a disaster risk model can account for the three dimensions of the UIP puzzle discussed above, we conduct a simple simulation exercise. Since our mechanism does not rely on risk aversion, we set $M_{t+\kappa}/M_{t+\kappa-j}=1$ for all $0<j<\kappa$.[19]

[18] In contrast, if we were looking at the term structure of expected carry trade returns, these would be driven by $\pi_{t+\kappa|t}-\pi_{t+j|t}$, which would depend on the particular process for innovations to transitory disaster probabilities, as in Lloyd and Marin (2019).

[19] Note that in (6) the discount factor (β) appears in both sides of the equation, to the same power. Therefore setting $\beta=1$ is without loss of generality.

We posit that, during a Peso event, annualised carry trade portfolios of all maturities deliver a loss of -100. This normalisation implies that the excess return outside of Peso events is given by 100 times the perceived probability of a Peso event. To calibrate $\pi_t^{\mathbb{P}}$, we draw on Farhi et al. (2015), who use currency options to elicit the probability of sudden crashes in the 1996-2014 period and find that disaster probabilities remain low, stable and close to zero until 2007—since then, they fluctuate dramatically, exceeding 25%. Consistently, we assume that $\log(\pi^{\mathbb{T}})$ follows an AR(1) process with $\rho = 0.9$ and normally distributed mean-zero innovations with $\sigma = 0.35$. We set $\pi_t^{\mathbb{P}} = 0.025$ in line with Barro (2006). Figure 3 (left) shows a simulation of short and long run, annualised carry trade returns, and Figure 3 (right), calculate the average term structure over the simulation.

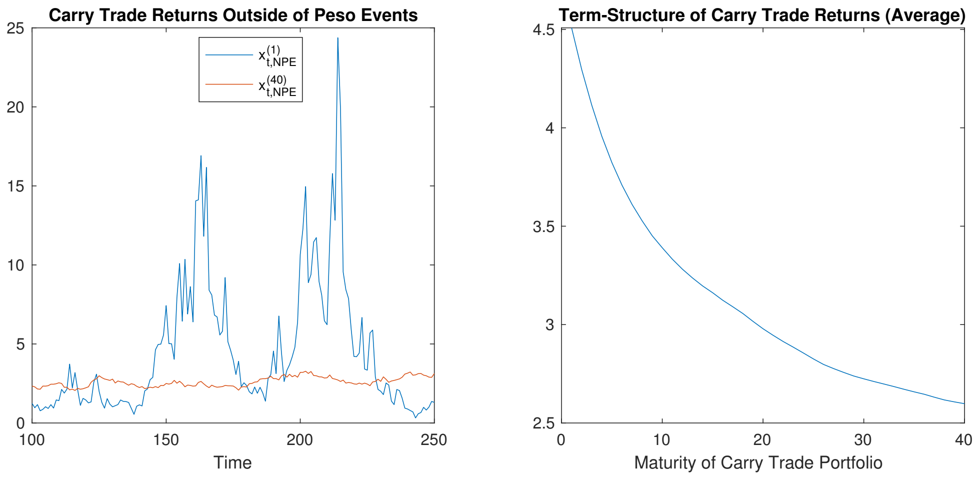


Figure 3: (Left) Ex-post carry trade returns outside of Peso event over a simulation of 250 periods. (Right) Sample average term structure of carry trade.

In our simulation, in each period t, a cohort of identical investors form κ carry trade portfolios, each consisting of $\kappa \in \{1, 2, ...T-1\}$ maturity bonds. Key to our result on the term structure of carry trade is that an investor purchasing a κ maturity bond at time t, expecting a payout at $t+\kappa$, prices in the probability of a Peso event according to $\pi_{t+\kappa|t}$, whereas an investor purchasing a one period bond at time $t+\kappa-1$ prices according to a probability $\pi_{t+\kappa|t+\kappa-1}$. If innovations to the probability process between t and $t+\kappa-1$ are mostly positive, then the term structure of carry trade is decreasing. Intuitively, agents forming expectations nearer to the disaster (when they purchase short maturity bonds) are more likely to attribute a higher probability to a disaster, than agents who formed expectations several periods earlier (when they purchased long maturity bonds).

In closing, two straightforward extensions of our framework warrant discussion. The first assumes a stochastic π_t^P, subject to the restrictions outlined above which serves to increase the volatility of long-maturity carry trade returns, helping the model to improve the fit with the evidence in Figure 2b. The second introduces a regime switching process, allowing for "high" and "low risk" periods (or periods of "risk on"-"risk off"), consistent with evidence from currency options in Farhi et al. (2015), such that $\pi_t = \pi_t^P + \mathbb{1}_t \pi_t^{\mathbb{T}}$, where $\mathbb{1}_t \in \{0, 1\}$.

4 Concluding Remarks

In the conventional textbook treatment, the Fama puzzle refers to the empirical finding that positive differentials systematically forecast an appreciation. In the time series of the pound-dollar currency pair over the past century, however, systematic excess appreciation of high yield currencies in normal times alternates with a reversal in the anomaly. A switch in the sign of the anomaly is a recurrent feature of the data, and thus neither specific to the Great Financial Crisis, nor, arguably, incongruent with existing theories. In this sense, a reversal in the UIP anomaly cannot be primarily attributed to the unconventional monetary policy pursued during the Great Financial Crisis.

A number of contributions have pursued the idea that the UIP anomaly could be explained by events that have large consequences on asset prices and wealth (hence on discount rates of investors), but occur with very small probability and may not materialize in finite samples. If we think of crises as the realization of such events, it is natural to think of reversals in the UIP puzzle as implied by no arbitrage pricing *conditional* on the economy being in a "peso event".

Our contribution consists of using a long time series with non-overlapping Peso events to articulate the UIP puzzle in three key empirical dimensions that should be jointly used to discipline theory: the failure of UIP during normal times at short investment horizons, the reversal in the Fama coefficient during crises and the relative success of the UIP hypothesis at long horizons. We show that a simple framework allowing for time-varying probability of a Peso event can go a long way in explaining these three dimensions of the UIP anomaly.

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5 Appendix: Supplementary Data

Figure 4. plots the returns to 1 year, 5 year and 10 year carry trade portfolios using zero coupon bond data for the USD-GBP currency pair, analogously to Figure 2. Data on interest rates are obtained from central banks and Wright (2011), as detailed in Lloyd and Marin (2019).

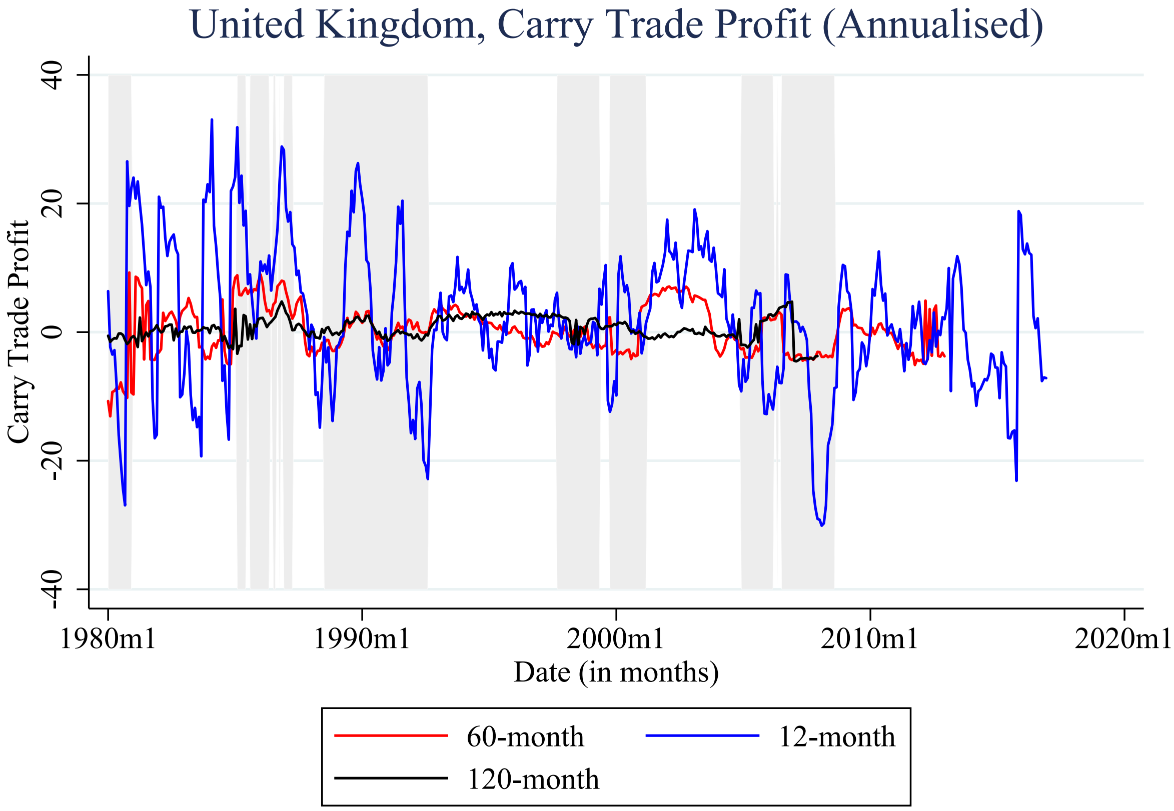

Figure 4: Log carry trade returns for USD-GBP currency pair, for maturities of 1, 5 and 10 years sing data from Lloyd and Marin (2019).