Crash-Neutral Currency Carry Trades

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Abstract

Currency carry trades exploiting violations of uncovered interest rate parity in G10 currencies deliver significant excess returns with annualized Sharpe equal to or greater than those of equity market factors (1990-2012). Using data on out-of-the-money foreign exchange options, I compute returns to crash-hedged portfolios and demonstrate that the high returns to carry trades are not due to peso problems. A comparison of the returns to hedged and unhedged trades indicates crash risk premia account for at most one-third of the excess return to currency carry trades.

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Currency carry trades are simple strategies designed to exploit violations of uncovered interest rate parity by investing in currencies with higher interest rates, while borrowing funds in currencies with lower interest rates. Over the period from 1990 to 2012, such strategies delivered Sharpe ratios between 0.40-0.55, matching or exceeding those of common equity market factors (Fama-French/Carhart). Simultaneously, carry trades have exhibited negatively skewed returns and a positive exposure to equity market downside risks, as captured by equity index put writing strategies. Taken together, these facts suggests that the excess returns to currency carry trades may reflect compensation for exposure to the risk of rapid devaluations of currencies with relatively higher interest rates. This paper investigates this hypothesis by constructing the returns to crash-hedged currency carry trades using a unique dataset of foreign exchange options, which includes all G10 cross-rates (45 currency pairs). A comparison of the returns to hedged and unhedged trades indicates that crash risk premia account for less than one-third of the total excess return earned by currency carry trades over this period.

Returns to currency carry trades are comprised of the *ex ante* known interest rate differential (carry), and an uncertain currency return component, capturing the change in the value of the long currency relative to the funding (short) currency. Uncovered interest parity (UIP) predicts that the currency return should exactly offset the interest rate differential, such that investors would be indifferent between holding the two currencies. In practice, this relationship is frequently violated, and currencies with relatively higher interest rates either appreciate, or do not depreciate sufficiently to offset the carry.[1] As a consequence, a carry trade investor in G10 currencies who went long (short) the currencies with the highest (lowest) one-month interest rates, weighting the positions in proportion to the interest rate differential, would have earned 5.21% *per annum* (t-stat: 2.62) over the period from 1990 to 2012 (Table I). However, these returns are punctated by infrequent, but severe episodes of rapid depreciations, which induce a negative skewness exceeding that of the equity market excess return.

I investigate the excess returns to currency carry trades in G10 currencies from the perspective of the associated FX option market, with the aim of addressing two questions.[2] First, do the high measured excess returns reflect a "peso problem" owing to the exposure to currency crash risks, which have not materialized – or, are insufficiently represented – in the sample? Second, to the extent that the high observed excess returns are not a reflection of a statistical measurement problem, what fraction of the excess return can be attributed to currency crash risk premia? To address these questions, I exploit a unique G10 exchange rate option panel dataset, which

[1] Froot and Thaler (1990), Lewis (1995), and Engel (2013) survey the vast theoretical and empirical literature on exchange rates. The leading explanations of UIP violations are generally subdivided into: exchange rate risk premiums, private information, near-rational expectations, and peso problems.

[2] Bates (1996) was the first to use currency option data to infer jump risks from dollar/yen and dollar/mark exchange rates. Bhansali (2007) scales interest differentials using FX option implied volatilities to assess the attractiveness of carry trades. Burnside, et al. (2011) and Farhi, et al. (2013) examine returns to currency carry trades hedged using X/USD options. Koijen, et al. (2012) study the dynamics of carry trades across different asset classes.

includes daily price quotes for all 45 cross-rate pairs at five distinct strikes, to construct crash-neutral currency carry trades in which the exposure to rapid depreciations in the relatively higher interest rate currency has been hedged using a put option overlay.[3] I then compare the returns to the unhedged currency carry trades with those of the corresponding FX option hedged portfolios.

First, I find that the excess returns to crash-hedged currency carry trades remain positive and statistically significant, indicating that "peso problems" (Rietz (1988)) are unlikely to provide an explanation for the high measured excess returns in G10 currencies. This finding contrasts with the results in Burnside, et al. (2011), and reflects two major differences in the identification strategy. First, unlike them I do not rely on options, which are at-the-money (50δ) to hedge crash risk, but rather focus attention on portfolios hedged using out-of-the-money (10δ) options. This results in higher estimates of the mean returns to the crash-hedged portfolios. Second, I hedge currency pairs (J/I) directly in their associated exchange rate option, rather than separately hedging the long and short legs of the trade using J/USD and I/USD options. This is a much more efficient hedging scheme, since it avoids paying for exposure to U.S. dollar risk in each option contract. I show that hedging using X/USD options produces downward biased estimates of crash-hedged returns, consistent with evidence of a U.S. dollar risk factor in the cross-section of currency returns (Lustig, et al. (2011, 2013)).

Second, I provide a simple, empirical decomposition of the excess returns to currency carry trade returns into diffusive and jump ("crash") risk premia. I show that the mean return to an appropriately constructed portfolio of crash-neutral currency carry trades provides an estimate of the diffusive risk premium, while the difference between the mean returns of the unhedged and hedged portfolios provides an estimates of the jump risk premium. The point estimates of the crash risk premium in G10 currencies range from 0.20% to 0.50% *per annum*, depending on the portfolio weighting and option hedging schemes, and account for less than 10% of the excess returns of the unhedged carry trade (Table III). These estimates are robust to the portfolio rebalancing frequency (monthly vs. quarterly), and the imposition of constraints on the net dollar exposure of the portfolio (non-dollar-neutral vs. dollar-neutral). The inclusion of a conservative estimate of option transaction costs – an ask-to-mid spread equal to 10% of the prevailing implied volatility – raises estimates of the crash risk premium to 1.3% to 1.6% *per annum*, or 20-30% of the total portfolio currency risk premium (Table V). In a related exercise, I show that in order to drive the point estimate of mean realized return of the hedged carry trade to zero, option-implied volatilities would have had to have been roughly 40% higher than the values reported in the data. These results

[3]The crash-hedged currency carry trades combine the position of the standard currency carry trade with a foreign exchange option struck at a fixed *delta*. This implies the option roughly has a fixed probability of expiring in-the-money, or equivalently, will be struck further away from at-the-money as option-implied volatilities increase. This construction reflects the view that a "crash" is a return realization, which is viewed as large from the perspective of an investor's *ex ante* assessment of volatility. In the robustness section, I also examine returns to carry trades hedged at fixed moneyness (Table VI).

indicate that, when viewed from the perspective of FX option prices, tail risks appear to play a modest role in determining currency risk premia.

Since the unhedged currency carry trade portfolio is a mimicking portfolio for the "slope" risk factor (Lustig, at al. (2013)), the analysis effectively provides a decomposition of the HML_{FX} risk premium in G10 currencies. However, it is crucial to highlight that this decomposition is not structural in nature, since I do not have an asset pricing model to estimate. Jurek and Xu (2013) address this concern by calibrating a multi-country model of stochastic discount factor dynamics inspired by the time-changed Lévy modeling framework of Carr and Wu (2004), which formally pins down currency dynamics, risk premia, and FX option prices.[4] Their analysis provides a time series of option-implied currency risk premia, and a formal decomposition of the instantaneous HML_{FX} risk premium across shock types (diffusive vs. jump) and the moments of the global shocks driving common variation in stochastic discount factors. They find evidence of low crash risk premia, consistent with the results of the empirical analysis presented here.

The analysis in this paper is thematically related to Farhi, et al. (2013), though I find evidence of much smaller crash risk risk premia. Specifically, they report that disaster risk premia account for "more than a third" of the currency risk premium accruing to currency carry trades, with a full-sample (1996-2011) estimate of the risk premium share of 46%. Their identification strategy is a hybrid of my empirical analysis and a calibration of a structural, jump-diffusion model, similar in spirit to Jurek and Xu (2013). Specifically, they estimate the total risk premium based on the mean historical *realized* return, and rely on an X/USD option pricing calibration to pin down the disaster risk premium. Their analysis faces two challenges. First, the calibration is done using only X/USD options, which does not allow for full identification of the common (global) and country specific components in the risk-neutral distributions. Bakshi, et al. (2008) show that this type of identification requires the availability of options on currency triangles (e.g. X/USD, Y/USD, *and* X/Y) and/or options with multiple tenors. Second, their model assumes that the only source of non-Gaussian innovations are jumps in the global factor, ruling out contributions from country-specific jumps. This results in an upward bias in the amount of option-implied, non-Gaussianity attributed to the priced, global component, and therefore higher estimates of jump risk premia. By contrast, the model in Jurek and Xu (2013) is calibrated to the full panel of 45 cross-rate options, and allows for jumps in both global and country-specific innovations driving stochastic discount factors.

Finally, given the evidence of low jump risk premia in G10 currencies, I ask whether the exchange range options used to construct the hedged carry trades are "cheap"? To address this issue I analyze the wedge between

[4] The model in Jurek and Xu (2013) drives the dynamics of country-level pricing kernels using a combination of common (global) and country-specific components, both of which follow jump-diffusions. The loading of each country on the global component is allowed to vary, consistent with the proportional asymmetries mechanism first proposed by Backus, et al. (2001). The model generalizes the framework in Lustig, et al. (2011) by allowing for non-Gaussian static distributions, matching the features of foreign exchange options.

measures of option-implied (risk-neutral) variance and skewness, and their realized counterparts (Table IV). I do not find evidence that the options are *unconditionally* cheap relative to the underlying exchange rate risks. In particular, I show that option-implied variance exceeds realized variance for most currency pairs, consistent with the presence of a variance risk premium (Della Corte, et al. (2011)). Similarly, I find evidence of skewness risk premia, whose sign is negatively related to the interest rate differentials. Interestingly, following positive returns to currency carry trades, *realized* skewness tends to become more negative, while *option-implied* skewness becomes more positive. This suggests that the price of insuring tail risk is *conditionally* lower following periods of high carry trade returns, even though the subsequent risk has increased.

The remainder of the paper is organized as follows. Section 1 reports summary statistics for G10 currency carry trades over the period 1990:1-2012:6, and a shorter sub-sample (1999:1-2012:6), matching the option dataset, and examines the returns from the perspective of equity market risk factors. Section 2 presents the construction of crash-neutral currency carry trades and the methodology underlying the empirical risk premium decomposition. Section 3 introduces the G10 FX option dataset, and discusses the relevant quoting conventions and nomenclature. Section 4 presents evidence on the returns to crash-neutral currency carry trades, provides estimates of the jump risk premium share in the total excess return, and reports the results of various robustness checks. Section 5 concludes. Appendix A discusses the computation of option-implied moments. A supplementary data appendix tabulates additional results.

1 Risks and Returns of Currency Carry Trades

Currency carry trades take advantage of violations of uncovered interest rate parity (UIP) by borrowing funds in currencies with low interest rates to purchase currencies with high interest rates. The basic unit of observation in the analysis of returns of these strategies is a currency pair excess return, which captures the net return to a zero-investment portfolio which borrows one unit of currency i, at interest rate $y^i_{t,t+\tau}$, to lend at short-term rate $y^j_{t,t+\tau}$ in market j. The short-term interest rates (yields) are expressed in annualized terms. At time t, the one unit of borrowed currency i buys $\frac{1}{S^{ji}_t}$ units of currency j, such that S^{ji}_t has the interpretation of the currency i price of one unit of currency j. Finally, at time $t+\tau$ the trade is unwound and the proceeds converted back to currency i, generating an excess return of:

$$r^{ji}_{t+\tau} = \exp\left(y^j_{t,t+\tau} \cdot \tau\right) \cdot \frac{S^{ji}_{t+\tau}}{S^{ji}_t} - \exp\left(y^i_{t,t+\tau} \cdot \tau\right) \quad (1)$$

The profit/loss from the trade can be roughly thought of as a combination of the interest rate differential (carry) and the realized currency return. Since the carry is known *ex ante*, and is riskless in the absence of counterparty risk, the sole source of risk in the carry trade stems from uncertainty regarding the realization of the future exchange rate, $S^{ji}_{t+\tau}$. In particular, the carry trade exposes the arbitrageur to rapid depreciations (crashes) of the currency which he is long *vis a vis* the funding currency. Under UIP, the forward price, $F^{ji}_{t,t+\tau} = S^{ji}_{t} \cdot \exp\left(\left(y^{i}_{t,t+\tau} - y^{j}_{t,t+\tau}\right) \cdot \tau\right)$, is an unbiased predictor of the future exchange rate, $S^{ji}_{t+\tau}$, such that carry trades earn a zero excess return in expectation. Unless otherwise noted, in the subsequent analysis I take the perspective of a U.S. dollar investor, reporting USD-denominated returns. If i is not the investor's home currency, the above return needs to be converted to the home currency (USD), h, by multiplying it by $\frac{S^{ih}_{t+\tau}}{S^{ih}_{t}}$.

To facilitate exposition, I report returns to various portfolio strategies rather than individual currency pairs. I focus attention on portfolios which: (1) take positions in all G10 currencies; (2) are re-balanced monthly; and, (3) apply simple cross-sectional weighting schemes.[5] Each of the portfolios is long (short) the currencies with the highest (lowest) interest rates as of time t. I report results for spread- and equal-weighted portfolios. For spread-weighted portfolios, the portfolio weights are assigned on the basis of the absolute distance of country i's interest rate, from the average of the the interest rates in countries with ranks five and six. If the portfolio is additionally required to be neutral with respect to the investor's domestic currency, the sum of the remaining nine weights is constrained to equal zero. The spread-weighting procedure is similar in spirit to forming portfolios of currencies based on interest rate sorts, and computing a long-short return between the extremal portfolios, but is more pragmatic given the small cross-section. As such, the spread-weighted, dollar-neutral carry trade portfolio can be thought of as the factor mimicking portfolio for the HML_{FX} factor (Lustig, et al. (2011)) in G10 currencies.

Panel A of Table I reports the historical U.S. dollar returns to simple carry trade strategies implemented in G10 currencies over two periods (1990:1-2012:6 and 1999:1-2012:6), the shorter of which corresponds to the span of the FX option data. The mean return over the full sample is 5.21% (t-stat: 2.62) for the spread-weighted portfolio and 3.36% (t-stat: 2.39) for the equal-weighted portfolio, and – in both cases – is essentially entirely accounted for by the interest rate carry component of the currency excess return. These mechanical strategies deliver Sharpe ratios exceeding those of all four Fama-French/Carhart equity market risk factors during this period, and exhibit non-normal returns with high, negative skewness. For example, the single worst monthly return is roughly 2.5 times larger than the average annualized risk premium. Adjusting for the effects of stochastic volatility using

[5]The G10 currency set is comprised of the Australian dollar (AUD), Canadian dollar (CAN), Swiss franc (CHF), Euro (EUR), U.K. pound (GBP), Japanese yen (JPY), Norwegian kronor (NOK), New Zealand dollar (NZD), Swedish krone (SEK), and the U.S. dollar (USD). There are a total of 45 possible cross-pairs.

the in-sample estimates of an EGARCH(1, 1) model, the standardized monthly (log) return innovations remain non-Gaussian, consistent with the presence of jumps (Panel B of Table I). The Jarque-Bera test rejects the null of Gaussianity both for the returns and standardized log returns.[6] These features carry over largely unchanged to the shorter, thirteen-year sample starting in 1999, which forms the basis for the analysis in Section 4.

For the full sample (1990-2012), the smallest standardized monthly return realization (Z-score) is -4.2 (spread-weighted, non-dollar-neutral carry trade portfolio), and occurs in the period *prior* to 1999. If I restrict attention to the second half of the sample (1999-2012), the smallest realized Z-score is -3.6 (equal-weighted, dollar-neutral carry trade portfolio). Under the null that standardized innovations are drawn from a Gaussian distribution, the probability of observing a minimum Z-score less than this in a 162-month dataset is 2.5%. For comparison, the corresponding minimum S&P 500 Z-score realizations during these two periods are only -3.1 (1990:1-2012:6) and -2.4 (1999:1-2012:6).[7]

The top panel of Figure 1 plots the cumulative returns to the spread-weighted carry trade portfolio over the full sample (1990:1-2012:6). The plot highlights both the high Sharpe ratio of the trade, and the -35% drawdown sustained during 2008. Crucial to note, the peak-to-trough loss is realized as a sequence of adverse returns, rather a single crash, such as October 1987 in equities. The bottom panel plots two measures of the contemporaneous portfolio return volatility, confirming the presence of stochastic volatility in carry trade returns. The first measure is an in-sample estimate of realized volatility based on an EGARCH(1, 1) model fitted to log portfolio returns. The second measure is an option-implied (risk-neutral) portfolio volatility, based on a full variance/covariance matrix of currency returns reconstructed from information on the full cross-section of 45 G10 currency options (1999:1-2012:6).

1.1 Dollar-neutrality

The mean returns of currency carry trades are somewhat sensitive to imposing the constraint of dollar-neutrality. This is consistent with evidence in Lustig, et al. (2013), which points to the existence of a U.S. dollar factor in the cross section of currency returns. In particular, imposing this constraint causes the mean returns to decline by 60-70 basis points *per annum*. This is evidenced in the top panel of Figure 1 which plots the total returns series for the spread-weighed carry trade portfolio over the period from 1999:1-2012:6 with and

[6] Brunnermeier, Nagel and Pedersen (2009) argue that realized skewness is related to rapid unwinds of carry trade positions, precipitated by shocks to funding liquidity. Plantin and Shin (2011) provide a game-theoretic motivation of how strategic complementarities, which lead to crowding in carry trades, can generate currency crashes. Chernov, Graveline, and Zviadadze (2012) use a combination of historical returns and option data to estimate stochastic volatility jump-diffusion models capturing these empirical features.

[7] To compute Z-scores monthly log index returns are scaled by $x \cdot \sqrt{1/12} \cdot \sigma_{t-}$, where σ_{t-} is the level of the CBOE VIX index as of the previous month end, and $x = 0.8$ is a scalar accounting for volatility risk premia embedded in the VIX level (Jurek and Stafford (2013)).

without the dollar-neutrality constraint. The return differential can be traced to the fact that both the spread- and equal-weighted portfolios exhibited a negative average net exposure to the U.S. dollar in a period during which the U.S. dollar depreciated relative to the G10 basket (Table A.I). Put differently, the U.S. dollar tended to be a low-interest rate, funding currency over the period from 1990-2012, contributing positively to the portfolio currency return.

To ensure the robustness of the results I report mean returns to currency carry trades with and without imposing the constraint of dollar neutrality. The virtue of the non-dollar-neutral carry trade portfolios is that their composition is independent of the home currency of the investor. By contrast, the analysis for the dollar-neutral portfolios ensures that the paper's main results are not affected by the net dollar exposure of the carry trade portfolio and the pricing of the dollar factor. More generally, stochastic discount factor models of currency dynamics (Backus, et al. (2001), Carr and Wu (2007), Lustig, et al. (2011), Farhi, et al. (2013), Jurek and Xu (2013)), predict that investors will demand a risk premium for being short their home currency. As such, one could envision constructing carry trade portfolios which are neutral with respect to each of the ten G10 currencies. I take the particular perspective of the U.S. investor, and construct dollar-neutral portfolios.[8]

1.2 Relation to equity factors

Table II explores the relation of currency carry trades to the four Fama-French/Carhart equity risk factors, and a mechanical S&P 500 index put-writing strategy (downside risk index, DRI). The put-writing strategy sells short-dated options, whose strike is one standard deviation out-of-the-money (roughly constant -0.2 delta), and posts half of the option strike price in cash as margin capital. This strategy is discussed in detail in Jurek and Stafford (2013), where it is shown to accurately match the *pre-fee* risks and returns of broad hedge fund indices such as the HFRI Fund-Weighted Composite and the Credit Suisse Broad Hedge Fund Index.[9]

Panel A of Table II reports the summary statistics of the monthly time series of the five risk factors. All factors have positive mean risk premia, though only the mean of the downside risk index (DRI) is statistically distinguishable from zero at the 5% significance level, despite a twenty-two year sample. The Sharpe ratios range from 0.2 for the size and value factors, 0.4 for the market and momentum factors, and 1.3 for the downside risk index. The market factor, momentum, and the downside risk factors all exhibit skewness values which are

[8]Another dimension through which the U.S. dollar can affect the portfolio formation process is if currencies are sorted into long and short portfolios on the basis of their interest rate differential relative to the U.S. dollar interest rate, rather than the average of the interest rates in countries with ranks five and six. Sorting relative to the home interest rate is potentially undesirable in that investors in different countries will identify different carry trade portfolios, depending on the level of their home interest rate. I relegate results for carry trade portfolios formed on the basis of interest rate differential relative to the U.S. interest rate to the appendix (Table A.II).

[9]The strategy is labeled $[Z = -1, L = 2]$ in Jurek and Stafford (2013), and its time series is extended to the beginning of 1990 by splicing data from the Berkeley Options Database (1986:1-1989:12) with OptionMetrics (1996:1-2012:6).

negative and statistically significant at the 1% level.

To examine the relation between currency carry trade returns and equity market risk factors I regress the excess returns of the spread-weighted strategies onto the four Fama-French/Carhart factors, and separately, the downside risk index (Panel B of Table II). The non-dollar-neutral and dollar-neutral strategies consistently exhibit positive loadings on the equity market (RMRF) and value (HML) factors in both subsamples. The intercepts are positive and statistically significant at the 10% level for the non-dollar-neutral strategies, and positive, but insignificant for the dollar-neutral strategies. The adjusted regression R^2 are above 10% in the full-sample, and above 25% in the 1999-2012 sample. The relation between carry trade returns and equity market returns is further revealed by the regression onto the put writing strategy (DRI), which indicates a statistically significant exposure to equity downside risk. For example, the spread-weighted, dollar-neutral carry trade portfolio has downside risk betas of 0.33 (t-stat: 5.85; 1990-2012) and 0.44 (t-stat: 7.76; 1999-2012). Furthermore, the intercepts in these regressions are negative and statistically indistinguishable from zero.

The regressions onto the S&P 500 index put-writing strategy confirm a strong exposure to equity downside risk, and indicate that after adjusting for this exposure currency carry trades do not offer positive abnormal returns. The regression evidence presented here complements results reported by Lettau, et al. (2013), who argue that currency carry trades exhibit an asymmetric CAPM beta, which is larger for downside moves than for upside moves, coinciding with variation in equity market risk premia. Lustig, et al. (2011) report that high (low) interest rate countries tend to offer low (high) returns when equity volatility increases, and that the loadings on the global equity volatility factor exhibit a similar pattern to HML_{FX} factor loadings. This evidence is consistent with the strong link between carry trade portfolio returns, and the put writing strategy, which is explicitly short equity volatility risk. Caballero and Doyle (2012) similarly report that carry trade returns are highly correlated with the returns of a strategy which shorts VIX futures. The positive exposure to the equity market downside risk suggests that extreme negative shocks to the currency carry trade are likely to coincide with large equity market declines (and increased volatility) and therefore adverse shocks to marginal utility.

2 Crash-Neutral Currency Carry Trades

Given the compelling evidence of negative skewness in currency carry returns (Table I) and its relation to equity market downside risk (Table II), I turn to the examination of the pricing of tail risks in currency markets. To do so, I construct simple crash-neutral currency carry trade strategies using foreign exchange options. These crash-hedged trades combine the positions of the standard currency carry trade with foreign exchange options to eliminate the risk of extreme negative realizations stemming from the depreciation (appreciation) of the high (low) interest rate currencies, beyond the option's strike price. A comparison of the returns between unhedged trades and hedged trades provides an simple and intuitive assessment of the pricing of tail risks.

Unlike previous papers, which relied exclusively on X/USD options, I exploit the full cross-section of the 45 G10 cross-rate options.[10] This yields two empirical advantages. First, since variances and higher-order moments are not linear combinations of one another, cross-rate options carry non-redundant information about correlations and tail risks in currency markets. Second, given evidence of a U.S. dollar factor in the cross-section of currency returns (Lustig, et al. (2013)) hedging a carry trade which is long currency J and short currency I using options on the J/I exchange rate will be more cost efficient that hedging the two legs using a combination of J/USD and I/USD options. Intuitively, an investor reliant on the portfolio of X/USD options pays for U.S. dollar risk exposure in each individual option, even though the position he is interested in hedging may have no dollar exposure itself. This biases the returns to the hedged positions downward, resulting in upward biased estimates of currency trail risk premia.

2.1 Hedged currency pair returns

The crash-hedged trades are constructed to have two features: (1) conditional on the option protection expiring in-the-money all currency risk exposure is eliminated; and, (2) at initiation the currency exposure of the crash-neutral portfolio matches that of the standard carry trade (i.e. the option overlay is hedged). As I show in the subsequent section, hedging the option overlay allows me to conveniently interpret the mean return of the crash-hedged portfolio as an estimate of the diffusive currency risk premium.

Without loss of generality, whenever I refer to an exchange rate, S_t^{ji} – the price of one unit of currency J in units of currency I – I adopt the convention that currency J has the higher interest rate, such that it is the long leg in the currency carry trade, as in (1). Therefore, in order to mitigate the downside of the carry trade (i.e. the risk of a sudden depreciation), the hedged portfolio will always involve the purchase of *put* options on the J/I exchange rate. In the event that the FX options are quoted in the opposing convention – as claims on the I/J exchange rate – I rely on the *foreign-domestic symmetry* property to compute the price of the relevant J/I put option. Specifically, this property relates the prices of call options on the I/J exchange rate, S_t^{ij}, to the prices of put options on the inverse, J/I, exchange rate S_t^{ji}. Without this convention, hedging carry trade crashes would require the purchase of call options, whenever the interest rate in currency J was lower than for currency I. In these circumstances, the carry trader would be short currency J, and the relevant concern would be a sudden

[10] Burnside et al. (2011) examine the returns to G10 currency carry trades hedged using *at-the-money X/USD options*. Farhi, et al. (2013) estimate a rare-disasters models using *X/USD options* with strikes spanning from 10δ puts to 10δ calls. An earlier draft of this paper also focused on returns to portfolios of currency carry trades hedged using X/USD options.

appreciation of the low interest rate (funding) currency.

To describe the composition of the hedged carry trade portfolio consider again the currency pair J/I, with J having the higher interest rate. The hedged portfolio involves a long position in currency J, funded in currency I, and a position in put options on the S_t^{ji} exchange rate. To protect against the risk of depreciation of currency J against currency I, assume the trader purchases FX puts with a strike price K_p at a cost of $\mathcal{P}_t(K_p, \tau)$ per put. For every q_p puts purchased, the trader must also purchase an additional $-q_p \cdot \delta_p$ units of the foreign currency to hedge the (negative) delta of the put options. Finally, I assume the purchase price of the puts is covered by borrowing additional funds in currency I. At time $t+1$ the return on this portfolio is given by:

$$\begin{aligned} \tilde{r}_{t+\tau}^{ji} &= \exp\left(y_{t,t+\tau}^{j} \cdot \tau\right) \cdot (1 - q_p \cdot \delta_p) \cdot \frac{S_{t+\tau}^{ji}}{S_t^{ji}} + q_p \cdot \max\left(\frac{K_p}{S_t^{ji}} - \frac{S_{t+\tau}^{ji}}{S_t^{ji}}, 0\right) - \\ & \quad - \exp\left(y_{t,t+\tau}^{i} \cdot \tau\right) \cdot \left((1 - q_p \cdot \delta_p) + q_p \cdot \frac{\mathcal{P}_t(K_p, \tau)}{S_t^{ji}}\right) \end{aligned} \tag{2}$$

In order to eliminate all currency exposure below the strike price, K_p, the quantity of puts must satisfy,

$$q_p = \exp\left(y_{t,t+\tau}^{j} \cdot \tau\right) \cdot (1 - q_p \cdot \delta_p) \quad \rightarrow \quad q_p = \frac{\exp\left(y_{t,t+\tau}^{j} \cdot \tau\right)}{1 + \exp\left(y_{t,t+\tau}^{j} \cdot \tau\right) \cdot \delta_p} \tag{3}$$

With the above quantity restriction, the return equation can be re-expressed as:

$$\begin{aligned} \tilde{r}_{t+\tau}^{ji} &= q_p \cdot \max\left(\frac{K_p}{S_t^{ji}}, \frac{S_{t+\tau}^{ji}}{S_t^{ji}}\right) - \exp\left(y_{t,t+\tau}^{i} \cdot \tau\right) \cdot \left((1 - q_p \cdot \delta_p) + q_p \cdot \frac{\mathcal{P}_t(K_p, \tau)}{S_t^{ji}}\right) \\ &= q_p \cdot \max\left(\frac{S_{t+\tau}^{ji} - K_p}{S_t^{ji}}, 0\right) - q_p \cdot \exp\left(y_{t,t+\tau}^{i} \cdot \tau\right) \cdot \frac{\mathcal{C}_t(K_p, \tau)}{S_t^{ji}} \end{aligned} \tag{4}$$

This expression makes transparent that the return to the strategy is bounded from below, and that for terminal realizations of the exchange rate that are above the strike, K_p, the strategy payoff response is steeper than in the unhedged carry trade, reflecting the hedging of the option overlay. Specifically, the upside sensitivity is magnified by a factor, $\frac{q_p}{\exp\left(y_{t,t+\tau}^{j} \cdot \tau\right)}$, which is strictly greater than one. To obtain the return of the trade in which the option overlay is not hedged (or the strike of the put converges to zero), the hedge delta, δ_p, in the above formula should be set to zero. As before, if i is not the investor's home currency, the above return needs to converted to the home currency, h, by multiplying it by $\frac{S_{t+\tau}^{ih}}{S_t^{ih}}$.

2.1.1 Portfolio hedging schemes

The empirical analysis focuses on the returns to spread- and equal-weighted portfolios of currency carry trades, which have been hedged using FX options. Since the long and short legs of the underlying currency portfolio are comprised of multiple currencies, there will generally be a number of potential combinations of X/Y options ($X \in long$, $Y \in short$) that can be used to implement the option hedge. I focus on two portfolio hedging schemes, which I refer to as *hierarchical* and *combinatorial* hedging.

After assigning weights to the long and short currencies in the unhedged currency carry trade portfolios, the hierarchical hedging scheme matches currencies in order of decreasing portfolio share. For example, the highest weighted long and short exposures are paired and hedged using the corresponding FX option. Any residual weight in the long (short) currency is then matched against the next highest weighted short (long) currency, and so on. This procedure continues until the currency weights in the long and short portfolio are exhausted. This hedging scheme is relatively efficient since it uses a small number of unique options, avoiding potential fixed costs of transacting in multiple contracts.

The combinatorial hedging scheme combines each currency in the long side of the portfolio with each currency in the short side of the portfolio, and weights them according to the cross-product of the long and short currency portfolio weights. This hedging scheme clearly uses a much larger number of contracts. For example, the maximum number of possible pairings for the non-dollar neutral portfolios is 45 $(= \frac{10 \cdot 9}{2})$, and 36 $(= \frac{9 \cdot 8}{2})$ – for the dollar-neutral portfolios. In practice, this scheme would potentially face higher fixed costs by trading in more distinct contracts, but may also benefit from lower price impact by splitting the hedge across more pairs. Finally, for comparison with results reported in Burnside, et al. (2011) and Farhi, et al. (2013), I consider a combinatorial X/USD hedging scheme in which each long and short currency is hedged individually using the corresponding X/USD options.

2.2 Computing the jump risk premium contribution

Suppose that currencies are exposed to a combination of diffusive and jump shocks ("crashes"), with the jump shocks contributing mass to the far left tail of the distribution, as in the "rare disasters" intuition (Barro (2006), Farhi and Gabaix (2011)). The total risk premium of currency exposure is the sum of premia for exposure to diffusive (λ^d) and jump (λ^j) shocks (e.g. see Carr and Wu (2007) and Jurek and Xu (2013) for a formal decomposition). In the absence of peso problems, the mean return of the *unhedged* currency carry trade portfolio provides an unbiased estimate of the sum of these two premia, $\lambda^u = \lambda^d + \lambda^j$, and is otherwise an upward biased estimator. More formally, this premium reflects compensation for a unhedged exposure of $\exp\left(y^j_{t,t+\tau} \cdot \tau\right)$ units of foreign currency at time $t+1$, as can be seen from the expression for the return of the unhedged trade, (1).

By contrast, the crash-hedged portfolio is effectively long q_p units of foreign currency, and is protected against the risk of depreciations in the S^{ji} exchange rate by the q_p put options with delta $\delta_p < 0$. The risk premium accruing to the q_p units of foreign currency is proportional to that of the unhedged trade, but is $\frac{q_p}{\exp\left(y^j_{t,t+\tau}\cdot\tau\right)}$ times greater. However, since each unit of currency exposure is mated with a put option – which hedges a fraction $|\delta_p|$ of the diffusive risk and all of the jump risk – the risk premium per unit of *hedged* exposure is, $\lambda^u - \left(|\delta_p|\cdot\lambda^d + \lambda^j\right)$, or equivalently, $(1-|\delta_p|)\cdot\lambda^d$. Another intuitive way to understand this representation is to note that the payoff representation (4), corresponds to q_p calls on the exchange rate. Each call is in-the-money, and earns the a fraction $(1-\delta_c)$ of the diffusive risk premium, but is not exposed to the risk of crashes, and therefore does not earn the jump risk premium. Consequently, the mean return on the crash hedged portfolio provides an estimate of:

$$\lambda^h \;=\; \frac{q_p}{\exp\left(y^j_{t,t+\tau}\cdot\tau\right)}\cdot(1-|\delta_p|)\cdot\lambda^d = \frac{1+\delta_p}{1+\exp\left(y^j_{t,t+\tau}\cdot\tau\right)\cdot\delta_p}\cdot\lambda^d \tag{5}$$

Since $y^j_{t,t+\tau}\cdot\tau \approx 0$, the denominator is very well approximated by $1+\delta_p$, such that the mean excess return of the crash-hedged portfolio provides an estimate of the diffusive component of the currency risk premium, $\lambda^h \approx \lambda^d$. Finally, I obtain an estimate of the jump risk premium, λ^j, by subtracting the mean excess return of the hedged trade (λ^h) from the unhedged trade (λ^u). I report estimates of the jump risk premium, as well as, its share in the total risk premium, $\phi = \frac{\lambda^u-\lambda^h}{\lambda^u}$. Crucially, note that peso problems induce an *upward* bias in the share estimate by biasing the unhedged return upward. Consequently, the ϕ values I report provide an upper bound on the population value of share of the currency risk premium attributable to jump risks.

Burnside, et al. (2011) and Farhi, et al. (2013) implement a related trade construction, which does not hedge the option overlay. Specifically, the unhedged position is mated with a single put option struck at delta, δ_p, such that the hedged trade earns a risk premium of $\tilde{\lambda}^h = (1+\delta_p)\cdot\lambda^d$. Burnside, et al. (2011) report the difference in mean returns, $\lambda^u - \tilde{\lambda}^h$, between the hedged and unhedged trades constructed this way using at-the-money options. Since this value is an empirical estimate of, $\lambda^j - \delta_p\cdot\lambda^d$, it provides an upward biased assessment of the jump risk premium, particularly when implemented using at-the-money options. Farhi, et al. (2013) correct this construction, and lever the returns of the hedged trades before subtracting them from the unhedged portfolios. Conceptually, their construction is equivalent to ours, with the modification that leverage is applied to the portfolio returns *ex post*, rather than being embedded in the portfolio construction *ex ante*, as done here.

Lastly, a crucial point to note is that for any of the aforementioned computations to provide an accurate approximation of the jump risk component of the total risk premium, the delta of the option hedge must be roughly constant over the life of the trade. In other words, empirical assessments of jump risk premia based on comparisons of realized returns to hedged and unhedged currency carry trades are likely to be more accurate for out-of-the-money option overlays, which have relatively low gamma. I therefore focus attention on carry trades hedged with the most out-of-the-money options available, and relegate results based on options closer to at-the-money to a supplementary data appendix.

3 Data

The key dataset used in the analysis includes price data on foreign exchange options covering the full cross-section of 45 G10 cross-pairs, spanning the period from January 1999 to June 2012. The dataset provides daily price quotes in the form of implied volatilities for European options at constant maturities and five strikes, and was obtained via J.P. Morgan DataQuery. In the empirical analysis I focus attention on constant-maturity one-month currency options, sampled at month ends ($N = 162$ months). For each day and currency pair, I have quotes for five options at fixed levels of option delta (10δ puts, 25δ puts, 50δ options, 25δ calls, and 10δ calls), which correspond to strikes below and above the prevailing forward price. In standard FX option nomenclature an option with a delta of δ is typically referred to as a $|100 \cdot \delta|$ option. In general, the delta of the option can be loosely interpreted as the probability of the option expiring in-the-money. Consequently, even the most out-of-the money options (10δ), should not be thought of as being extremely out of the money. The specifics of foreign exchange option conventions are further described in Wystup (2006) and Carr and Wu (2007). In general, an option on pair X/Y gives its owner the right to buy (sell) currency X at option expiration at an exchange rate corresponding to the strike price, which is expressed as the currency Y price of one unit of currency X. The remaining data I use includes one-month Eurocurrency (LIBOR) rates and daily exchange rates for the nine G10 currencies versus the U.S. dollar obtained from Reuters via Datastream.

3.1 FX option conventions

FX option prices are quoted in terms of their Garman-Kohlhagen (1983) implied volatilities, much like equity options are quoted in terms of their Black-Scholes (1973) implied volatilities. In fact, the Garman-Kohlhagen valuation formula is equivalent to the Black-Scholes formula adjusted for the fact that both currencies pay a continuous "dividend" given by their respective interest rates. Let S_t^{ji} denote the currency i price of one unit of currency j, and $r_{t,t+\tau}^i$ and $r_{t,t+\tau}^j$ be the risk-free rates of interest for horizon τ in the two countries. The price of a call and put option can be recovered from the following formulas:

$$\mathcal{C}_t\left(S_t^{ji}, K, \tau, y_{t,t+\tau}^i, y_{t,t+\tau}^j\right) = \exp\left(-y_{t,t+\tau}^i \cdot \tau\right) \cdot \left[F_{t,\tau} \cdot N(d_1) - K \cdot N(d_2)\right] \quad (6a)$$

$$\mathcal{P}_t\left(S_t^{ji}, K, \tau, y_{t,t+\tau}^i, y_{t,t+\tau}^j\right) = \exp\left(-y_{t,t+\tau}^i \cdot \tau\right) \cdot \left[K \cdot N(-d_2) - F_{t,\tau} \cdot N(-d_1)\right] \quad (6b)$$

where:

$$d_1 = \frac{\ln F_{t,t+\tau}^{ji}/K}{\sigma_t(K,\tau) \cdot \sqrt{\tau}} + \frac{1}{2} \cdot \sigma_t(K,\tau) \cdot \sqrt{\tau} \qquad d_2 = d_1 - \sigma_t(K,\tau) \cdot \sqrt{\tau} \quad (7)$$

and $F_{t,\tau}^{ji} = S_t^{ji} \cdot \exp\left\{(y_{t,t+\tau}^i - y_{t,t+\tau}^j) \cdot \tau\right\}$ is the forward rate for currency to be delivered τ periods forward. The forward rate is determined through the covered interest parity condition, which is no-arbitrage relationship which must hold at time t. Akram, Rine and Sarno (2009) find that violations of covered interest parity are confined to very high frequencies, and are essentially never violated at the daily and lower horizons. The implied volatilities necessary to match the price of the τ-period options will generally depend on the option's strike value, K, and are denoted by $\sigma_t(K,\tau)$.

Unlike equity options which have fixed calendar expiration dates and are quoted at fixed strike prices, foreign exchange options are generally quoted at constant maturities and fixed deltas. The most frequently traded options have maturities of 1M, 3M, 6M an 1Y, and include at-the-money (50δ) options, as well as, 25δ and 10δ calls and puts. More precisely, market makers quote prices of portfolios of 25δ and 10δ options (risk reversals and butterfly spreads), as well as, an at-the-money delta-neutral straddle; see Wystup (2006) for details. The strike price of the straddle, for any given maturity, is chosen such that the deltas of a put and call at that strike are equal, but of opposite sign. From these data, one can compute implied volatilities at five strike values.

The option deltas, obtained by differentiating the option value with respect to the spot exchange rate, S_t^{ji}, are given by,

$$\delta_c(K) = \exp\left(-y_{t,t+\tau}^j \cdot \tau\right) \cdot N(d_1) \quad (8a)$$

$$\delta_p(K) = -\exp\left(-y_{t,t+\tau}^j \cdot \tau\right) \cdot N(-d_1) \quad (8b)$$

allowing for conversion between the strike price of an option and its corresponding delta. Specifically, the strike prices of puts and calls with delta values of δ_p and δ_c, respectively, are given by:

$$K_{\delta_c} = F^{ji}_{t,t+\tau} \cdot \exp\left(\frac{1}{2} \cdot \sigma_t(\delta_c)^2 \cdot \tau - \sigma_t(\delta_c) \cdot \sqrt{\tau} \cdot N^{-1}\left[\exp(y^j_{t,t+\tau} \cdot \tau) \cdot \delta_c\right]\right) \tag{9a}$$

$$K_{\delta_p} = F^{ji}_{t,t+\tau} \cdot \exp\left(\frac{1}{2} \cdot \sigma_t(\delta_p)^2 \cdot \tau + \sigma_t(\delta_p) \cdot \sqrt{\tau} \cdot N^{-1}\left[-\exp(y^j_{t,t+\tau} \cdot \tau) \cdot \delta_p\right]\right) \tag{9b}$$

The strike price of the delta-neutral straddle is obtained by setting $\delta_c(K) + \delta_p(K) = 0$ and solving for K. It is straightforward to see that the options in this portfolio must satisfy $d_1 = 0$, and their corresponding strike is:

$$K_{\text{ATM}} = S_t \cdot \exp\left((y^i_{t,t+\tau} - y^j_{t,t+\tau}) \cdot \tau - \frac{1}{2} \cdot \sigma_t(\text{ATM})^2 \cdot \tau\right) = F^{ji}_{t,t+\tau} \cdot \exp\left(\frac{1}{2} \cdot \sigma_t(\text{ATM})^2 \cdot \tau\right) \tag{10}$$

Consequently, although the straddle volatility is described as "at-the-money," the corresponding option strike is neither equal to the spot price, nor the forward price.

Finally, an important feature of currency options, which allows me to focus on trades hedged exclusively using put options, is the so-called *foreign-domestic symmetry*, which states that:

$$\frac{1}{S^{ji}_t} \cdot \mathcal{C}_t\left(S^{ji}_t, K, \tau, y^i_{t,t+\tau}, y^j_{t,t+\tau}\right) = K \cdot \mathcal{P}_t\left(\frac{1}{S^{ji}_t}, \frac{1}{K}, \tau, y^j_{t,t+\tau}, y^i_{t,t+\tau}\right) \tag{11}$$

or, equivalently,

$$\frac{1}{S^{ji}_t} \cdot \mathcal{P}_t\left(S^{ji}_t, K, \tau, y^i_{t,t+\tau}, y^j_{t,t+\tau}\right) = K \cdot \mathcal{C}_t\left(\frac{1}{S^{ji}_t}, \frac{1}{K}, \tau, y^j_{t,t+\tau}, y^i_{t,t+\tau}\right) \tag{12}$$

I frequently make use of this relationship in computing the returns to crash-hedged currency carry portfolios. For example, suppose the trade includes the AUD/JPY currency pair and requires the purchase of put options, but options are quoted in the JPY/AUD convention. The above relationship allows me to compute the price of the necessary AUD/JPY put, from the prices of JPY/AUD call options.

3.2 Summary statistics

The first thing to note about the cross-section of the FX options is that the 10δ options are not particularly far out-of-the-money. When measured in terms of their standardized moneyness, which reflects the return Z-score necessary for the option to expire in-the-money $\left(\frac{1}{\sigma_t(ATM)\cdot\sqrt{\tau}} \cdot \ln \frac{K}{F^{ji}_{t,t+\tau}}\right)$, the strike prices of these puts (calls) are approximately 1.4 monthly standard deviations below (above) the prevailing forward price.[11] Consequently, there is a meaningful chance that these options expire in-the-money as a result of the accumulation of small, diffusive shocks, rather than solely as a result of a large jump.

Since there is a large amount of data to summarize (currency pair x option strike x day), I focus on reporting summary statistics for the risk-neutral moments implied by the option prices. This effectively collapses the cross-section of strikes into statistically interpretable measures characterizing the risk-neutral distribution. This approach offers an important advantage relative to studying market quotes directly, e.g. using the difference of put and call implied volatilities (risk-reversals) as a metric for skewness, since their implications for risk-neutral moments depend on the prevailing level of the option-implied volatility curve. The cost of focusing on risk-neutral moments is that it requires data augmentation – interpolating the implied volatilities between the observed quotes, and extrapolating the implied volatilities outside of the observed quotes. Specifically, I interpolate the implied volatility curve on each day for each currency pair using the vanna-volga scheme (Castagna and Mercurio (2007)), and *conservatively* append flat tails to the implied volatility curve beyond the last observed strike point (10δ). I then compute the risk-neutral variance, skewness and kurtosis of the option-implied distribution using the results from Bakshi, et al. (2003). Details of this procedure are presented in Appendix A.

Figure 2 presents scatter plots of the cross-sectional relationship between the mean interest rate differential and the mean estimates of risk-neutral moments. The left panel illustrates that the mean pair-level option-implied volatility is on the order of 10% and exhibits a slight V-shaped pattern relative to the interest rate differential. The mean level of option implied-skewness ranges from -0.45 (AUD/JPY, NZD/JPY) to 0.35 (JPY/USD) in the cross-section, and exhibits a strong negative relation relative to the mean currency pair-level interest rate differential ($\hat{\beta} = -10.1$, t-stat: -13.4, Adj. R^2: 80.3%). The modest magnitudes of the option-implied skewness in part reflect the conservative nature of the extrapolation scheme, which appends flat tails to the implied volatility curve beyond the 10δ strike. However, even if the observed implied volatility functions were extrapolated to the 1δ level using the vanna-volga scheme before appending the flat tails, the mean option-implied skewness values would only range from -0.6 to 0.4. These values remain smaller than the *realized* skewness of the carry trade portfolio returns, or Z-scores (Table I). The strong negative cross-sectional relationship between the *mean* interest rate differential and the *mean* option-implied skewness is suggestive of a link between interest rates and: (a) the

[11] The standardized moneyness of the calls and puts is approximately equal to:

$$\begin{aligned} m_{\delta_c} &\approx \frac{\sigma_t(\delta_c)}{\sigma_t(ATM)} \cdot N^{-1}\left[\exp\left(y^j_{t,t+\tau}\cdot\tau\right)\cdot\delta_c\right] \\ m_{\delta_p} &\approx \frac{\sigma_t(\delta_p)}{\sigma_t(ATM)} \cdot N^{-1}\left[-\exp\left(y^j_{t,t+\tau}\cdot\tau\right)\cdot\delta_p\right] \end{aligned}$$

Using this computation, the strikes of the 25δ options are approximately 0.7 standard deviations away from the forward price, and the 10δ options are approximately 1.40 standard deviations away from the forward price.

quantity of crash-risk; and/or, (b) the price of crash risk. I return to this point in the discussion of the returns to crash-hedged carry trades in Section 4.

Finally, I present the data from a different perspective in Figure 3 by plotting the time-series means of the one-month option-implied volatility functions for the nine X/USD pairs. Before taking means the volatilities were re-scaled by the contemporaneous at-the-money values to provide a scale free representation. The red (blue) lines correspond to periods in which the foreign short-term interest rate was above (below) the US short-term interest rate. The figure clearly illustrates that the option-implied exchange rate distributions of typical funding currencies (CHF, JPY) are generally positively skewed; while those of typical long currencies (AUD, NZD) are generally negatively skewed. Interestingly, the skewness of the option-implied distribution appears to be only weakly related to the interest rate differential. From the empirical perspective, this stands in contrast to the finding that realized skewness is negatively related to the interest rate differential (Brunnermeier, Nagel and Pedersen (2009)). From the theoretical perspective, risk-based explanations of the currency carry trade require the interest rate differential to reveal differences in loadings on a common, priced factor (Backus, et al. (2001), Lustig, et al. (2011)). If these loadings are time-varying, and the common factor has a non-Gaussian distribution (e.g. as in Carr and Wu (2008), Farhi and Gabaix (2011), Farhi, et al. (2013), Jurek and Xu (2013)), shifts in the interest rate differential would coincide with changes in the skew of the risk-neutral distribution. In particular, the skewness should change sign conditional on the sign of the interest rate differential, and exhibit negative (positive) skewness when the foreign interest rate is above (below) the U.S. rate. Despite the strong cross-sectional link between the mean level of skewness and the mean interest rate differentials, the time-series relationship appears to be quite weak.[12]

4 Risk Premia in G10 Currencies

Table III reports summary statistics for returns to hedged currency carry trades implemented in the G10 currency set over the period from January 1999 to June 2012. I compute buy-and-hold returns, rebalancing positions monthly, as in the unhedged currency carry trade described in Section 1. As before, I separately report the results for portfolios that are non-dollar-neutral and dollar-neutral. The individual currencies in the portfolios are spread-weighted and the trades are hedged using the most out-of-the-money options available in the J.P. Morgan data (10δ). As mentioned earlier, the accuracy of the currency risk premium decomposition based on

[12] In a panel regression with currency fixed effects, applied to the full cross-section of 45 G10 cross-rates sampled at one-month intervals, the slope of the relationship between option-implied skewness and the interest rate differential is only -0.86 (t-stat: -2.06). Although the panel R^2 is 47.7%, it drops to 0.3% when computed net of fixed effects, revealing the weak explanatory power of the interest rate differential in the time series dimension (unreported results). See also Table A.VII.

comparisons of returns to hedged and unhedged trades improves with the stability of the delta of the option hedge. I therefore focus on on low-gamma, out-of-the-money options, and relegate results based for portfolios hedged with 25δ and 50δ (at-the-money) options to the supplementary data appendix (Tables A.III and A.IV). I report results based on three option hedging schemes. The first hedging scheme – hierarchical hedging – uses the full set of 45 G10 cross rate options, and aims to hedge the portfolio using the fewest number of options possible. The second scheme – combinatorial hedging – also uses the full set of the cross rate options, but creates all possible pairings of long and short currencies. The final scheme is a variant of the combinatorial hedging scheme in which all currencies are hedged using the corresponding X/USD options. I report results based on this hedging scheme to facilitate comparisons with the literature, though regard it as a relatively inefficient way to hedge currency risk, given evidence of a U.S. dollar factor in currency returns (Lustig, et al. (2013)). For each hedging scheme, I report the average number of pairs in the portfolio at each point in time, the total number of unique currency pairs formed over the entire sample period, and the fraction of options expiring in-the-money.

Consistent with intuition, the hedged trades have less negative skewness, and realize less extreme downside returns, when compared with the unhedged currency portfolio. The skewness of the hedged portfolio returns is approximately -0.4 versus -1.1 for the unhedged portfolio, and the smallest realized monthly return increases by roughly 4%. The volatilities of the unhedged and hedged portfolios are comparable, reflecting the hedging of the option overlay, which equalizes the effective currency exposure at initiation. The mean returns to the hedged currency carry trades – which provide an estimate of the diffusive component of the currency risk premium – remain positive and significant at conventional significance levels, but deliver lower point estimates than the unhedged portfolio, consistent with the unhedged portfolio earning a jump risk premium. For example, the mean returns to the hierarchically and combinatorially hedged portfolios stand at 5.27% (t-stat: 2.08) and 5.36% (t-stat: 2.12) *per annum*. A comparison with the returns to the corresponding unhedged portfolio reveals a small, positive jump risk premium equal to 0.31% and 0.22% *per annum*, respectively, but the point estimates are statistically indistinguishable from zero. When measured as a fraction of the mean excess return of the unhedged portfolio, the jump risk premia account for 4-5.5% of the total risk premium.

Panel B of Table III compares the returns of hedged and unhedged currency carry trades after imposing the constraint of dollar-neutrality. This constraint lowers the portfolio return by removing the component of the return due to a net negative U.S. dollar exposure in the non-dollar-neutral portfolio over a period when the dollar depreciated against the G10 currency basket (Table A.II). The resulting unhedged, dollar-neutral portfolio represents a factor mimicking portfolio for the HML_{FX} factor in G10 currencies (Lustig, et al. (2011)), allowing me to decompose the factor risk premium into diffusive and jump components. I find that the hedged portfolio returns deliver an excess return of roughly 4.5% *per annum*, which is statistically greater than zero at the 5% significance level. Again, the hedged portfolios are less negatively skewed and realized less extreme downside returns. The difference between the returns of the unhedged and hedged portfolios indicates the jump risk premium of the HML_{FX} factor in G10 currencies is between 0.39% *per annum* (t-stat: 0.9; combinatorial hedging) and 0.51% *per annum* (t-stat: 1.1; hierarchical hedging). Expressed as a fraction of the excess return of the unhedged carry trade portfolio, these values account for 8-10% of the HML_{FX} risk premium. Overall, these results indicate that tail risks appear to play a modest role in determining currency risk premia, when viewed from the perspective of FX option prices.

Figure 4 illustrates these results by plotting the cumulative value of $1 investment in the spread-weighted non-dollar-neutral strategy over the period from January 1999 to June 2012 with and without hedging. The returns of the unhedged and hedged strategies are strikingly similar, with each trade sustaining a nearly 35% peak-to-trough drawdown during the Fall of 2008. These similarities owe to the fact that the option hedge is applied at fixed *delta*, rather than a fixed distance away from at the money. Consequently, when implied volatilities rise – as they did in the Fall of 2008 (Figure 1) – the options are struck further away from at-the-money, exposing the hedged trade to potentially larger losses. This is not a failure of the hedging scheme, but rather a reflection that this scheme defines a "crash" as an event that is large relative to the *ex ante* risk, e.g. as measured by the option-implied volatility. In the robustness section, I compute returns under a fixed moneyness hedging scheme, where "crashes" are interpreted as adverse return realizations, exceeding a threshold set without reference to the prevailing level of currency volatility.

To provide a different perspective on jump risk premia embedded in FX options, and to demonstrate how the fixed-delta crash hedging scheme is working, the bottom panel of Figure 4 plots the ratio of accumulated wealth under each hedged strategy to the wealth under the unhedged strategy. This ratio is anticipated to decline in periods when realized losses are smaller than implied by FX options, either due to high risk premia or a lack of adverse events. It will remain flat in periods where realized losses are similar to those implied by options, and rise – when realized losses exceed option-implied expectations, i.e. in "crash" events. The plot illustrates three points. First, it shows that over the full sample, the hedged strategies underperform the hedged strategy over the full sample, consistent with a positive, but small, jump risk premium, documented earlier. Second, it illustrates how the hedged strategies deployed in the full set of G10 cross-rate options outperform the unhedged strategy during the Fall of 2008, making up nearly a decade of accrued shortfall. Finally, the figure illustrates the inefficiency of the X/USD hedging strategy, which I discuss in more detail below.

4.1 Hedging with X/USD options

Earlier drafts of this paper, as well as, Burnside et al. (2011) and Farhi, et al. (2013), examine currency carry trades hedged using X/USD options. For example, rather than hedging the exposure of the AUD/JPY pair directly, these papers compute the returns to the hedged portfolio as the difference between the returns of a long position in AUD/USD hedged with AUD/USD options, and a short position in JPY/USD hedged with JPY/USD options. This hedging scheme is inefficient, since it pays for the volatility induced by USD exposure in both legs, even though the position of interest (AUD/JPY) has no USD exposure at all. This can also be readily seen in the context of the dollar-neutral currency carry trade portfolios. Though each long and short currency exposure can be hedged using X/USD options, the aggregate portfolio has no net U.S. dollar exposure, by construction. The inefficiency in the hedging scheme translates into lower returns on the hedged portfolios, and therefore a greater estimate of the currency jump risk premium, which is computed on the basis of the difference in the mean returns of the hedged and unhedged portfolio returns. Given Lustig, et al. (2013) find evidence indicative of a U.S. dollar factor in the cross section of currency returns, the magnitude of the resulting bias may be significant.

To evaluate the magnitude of this effect on estimates of the jump risk premium, I re-compute the returns to the crash-hedged currency portfolios relying on X/USD options for hedging. I report results for spread-weighted, 10δ hedged portfolios in Table IIIf, and relegate results for hedging schemes based on 25δ and 50δ to a supplementary data appendix. Consistent with intuition, the returns to carry trade portfolios hedged using X/USD options are lower than when portfolios are hedged using the full set of G10 cross-rate options (Figure 4). In turn, the estimate of the jump risk premium rises to 0.51% (non-dollar-neutral) and 0.69% (dollar-neutral) *per annum*, accounting for 9% and 14% of the unhedged portfolio returns, respectively. Though the estimates of the jump risk premium remain small in magnitude, they are roughly 50% higher than when computed on the basis of the hedging schemes utilizing the full set of G10 cross-rate options.

4.2 Equal-weighted portfolios

Farhi, et al. (2013) report that disaster risk premia account for "more than a third" of the currency risk premium accruing to currency carry trades, with a full-sample (1996-2011) estimate of the risk share of 46%. This estimate is considerably higher than the risk premium shares reported in this paper, and owes to a combination of: (a) hedging using X/USD options; and (b) equal-weighting currencies within the portfolios. Specifically, their estimate is based on sorting currencies into terciles on the basis of the prevailing interest rates, and then going long (short) an *equal-weighted* portfolio of the high (low) interest rate currencies. In the supplementary data appendix (Table A.V), I compute the returns to equal-weighted portfolios hedged using the full set of forty-five

G10 cross-rate options and the set of nine X/USD options. Consistent with their results, I find that hedging an equal-weighted portfolio of G10 currencies in X/USD options, indicates that the jump risk premium accounts for up to 27% of the total currency risk premium. However, these estimates are again roughly 50% higher than obtained under the more efficient hedging schemes utilizing the full set of cross-rate options.

4.3 Quarterly hedging

Standing at the beginning of the sample, an investor who was concerned about the risk of "crashes" – interpreted as extreme, rare events – but had no view on the prices of foreign exchange options would have plausibly been indifferent between buying one-month and three-month option protection. To evaluate the effect of the hedging frequency, I return to the spread-weighed, hierarchically-hedged carry trade portfolios and compare quarterly buy-and-hold returns with the compounded return from rolling-over one-month insurance (Table A.VI). The performance characteristics of the unhedged strategies turn out to be remarkably similar, suggesting that the effect of the lower rebalancing frequency on the carry trade itself is negligible. Similarly, the returns to the quarterly buy-and-hold hedged strategies are statistically indistinguishable from the compounded returns based on the monthly crash-hedged returns.[13] The comparison of quarterly returns to hedged and unhedged G10 carry trade portfolio indicates that jump risk premia account for 6-10% of the total portfolio currency risk premium, in line with the previous results.

4.4 Discussion and Robustness

The returns to crash-hedged currency carry trades indicate that jump risks account for less that 10% of the risk premium earned by the spread-weighted G10 carry trades. In this section I investigate whether this finding is driven by FX options being "cheap" relative to the realized risks in the underlying exchange rates, and examine its robustness with respect to the inclusion of transaction costs. Finally, I compare the baseline results with those obtained under hedging at fixed moneyness.

4.4.1 Are FX options cheap?

In the preceding analysis, the magnitude of the crash risk insurance premium embedded in FX option prices was measured in terms of its return consequence for a portfolio of currency carry trades. An alternative approach

[13] Inference regarding quarterly buy-and-hold options strategies is sensitive to the timing at which the option hedge is rolled (i.e. prior to or during a crisis event). The results reported here focus on strategies rebalanced at calendar quarter-ends (March, June, September, December). For example, the September 2008 rebalance occurs after implied volatilities experienced a twofold increase relative to their sample average up to that point. This results in the protection being struck relatively far out-of-the-money, thus forcing the hedged portfolio to absorb significant losses in 2008:Q4.

to assessing this risk premium is to examine the dynamics of the wedge between option-implied and realized moments of the currency return (e.g. variance and skewness). The availability of the full cross-section of 45 G10 options once again provides a unique perspective, since cross-rate options encode non-redundant information about the moments of the joint distribution of currency returns. The main drawback of this analysis, relative to the analysis of crash-hedged positions, is that the computation of the risk-neutral moments requires data augmentation (i.e. interpolation and extrapolation of implied volatility curves). The details of this procedure are described in Section 3.2 and Appendix A. By contrast, the computation of the crash-hedged returns relied exclusively on the tradable option price quotes provided by J.P. Morgan.

Figure 5 plots the mean differential between the option-implied and realized variance (left panel) and skewness (right panel), as a function of the mean one-month interest rate spread. The option-implied moments are computed using the methodology of Bakshi, et al. (2003), after interpolating the implied volatilities using the vanna-volga method (Castagna and Mercurio (2007)), and *conservatively* appending flat tails beyond the quoted 10δ put and call implied volatilities. The realized moments are computed using daily, intra-month currency excess returns. The left panel indicates that 33 out of 45 currency pairs exhibit a significant variance risk premium at the 5% significance level, and are additionally marked with red circles (mean t-statistic: 5.62). For all these currency pairs, the option-implied variance exceeds its realized counterpart, suggesting that – from the perspective of a risk-neutral investor – options are generally not "cheap." Similarly, I find that 24 out of 45 currency pairs exhibit a statistically significant skewness risk premium (5% significance level; mean (absolute) t-statistic: 5.23), measured as the wedge between option-implied and realized skewness. In all but two of these pairs (JPY/USD, JPY/SEK), the skewness risk premium is negative, suggesting investors have to pay a premium – relative to the actuarially fair price – for hedging depreciation risk. In the two remaining significant pairs, investors pay a premium for hedging appreciation risk. Consequently, the empirical evidence generally points to the presence of significant variance and skewness risk premia being embedded in FX option prices, consistent with evidence in Della Corte, et al. (2011).

Table IV explores the dynamics of realized and option-implied moments, as well as, the corresponding risk premia using regression analysis. The specification of each regression is such that it can be interpreted as a first-order autoregressive model for the dependent variable, which allows for a time-varying mean, whose magnitude is controlled by the currency pair fixed effect, the lagged currency excess return, and the one-month interest rate differential.[14] The regressions indicate that both realized variance ($Var^{\mathbb{P}}$) and option-implied variance ($Var^{\mathbb{Q}}$):

[14] Regressions in which the lagged value of the dependent variable is not included produce quantitatively similar coefficient estimates, though the R^2 values are generally lower (Table A.VII). The results are also robust to the details of the computation of the option-implied moments, and are qualitatively unaffected, if implied volatilities are first extrapolated to the 1δ put and call level, before appending flat implied volatility tails.

(a) have conditional means which decline following positive currency excess returns; (b) are higher for currency pairs with larger interest rate differentials (see also Figure 3); and, (c) have dynamics which exhibit low to moderate persistence at the monthly horizon. The explanatory power of the regression ranges from 13% (realized) to 52% (option-implied), with currency fixed effects playing an important role in capturing variation across the panel of currency pairs. The variance risk premium – the difference between the forward-looking option-implied variance and the subsequent realized variance – appears to be unrelated to past returns, the interest rate differentials, and is generally not persistent. The presence of unconditional variance risk premia (Figure 5, left panel) is captured by positive and statistically significant estimates of currency pair fixed effects, which have been suppressed to conserve space.

The dynamics of realized ($Skew^{\mathbb{P}}$) and option-implied ($Skew^{\mathbb{Q}}$) skewness are more nuanced. Both quantities have conditional means which are negatively related to the interest differential, with the risk-neutral skewness exhibiting persistence similar to the risk-neutral variance. The realized skewness does not exhibit persistence, though this likely owes to a large measurement error. More interestingly, the conditional means of the two skewness measures move in *opposing* directions in response to lagged currency returns. For example, consider a prototypical currency carry trade pair, such as AUD/JPY. Following periods of positive currency excess returns (following the success of carry trades), the risk of crashes increases ($Skew^{\mathbb{P}}$ becomes more negative), while the cost of insuring against those events declines ($Skew^{\mathbb{Q}}$ becomes less negative). Taken together these findings imply that the wedge between the risk-neural and realized skewness is a positive function of the past realized currency return, which is confirmed in the skewness risk premium regression ($\hat{\beta} = 4.20$, t-stat: 7.23). While the negative mean skewness risk premia (Figure 5) are consistent with crash risk being priced in FX option markets, the panel regressions suggest that the price of this insurance is *conditionally* lower in periods in which it is most valuable. This effect would increase the returns to crash-hedged currency carry trades, thus lowering the contribution of the jump risk component to the unhedged currency excess return.

Taken together, the empirical evidence on option-implied and realized moments, does not support the hypothesis that FX options are cheap relative to the underlying exchange rate risks. Unconditionally implied volatilities are never lower than realized volatilities, and investors pay a premium for insurance against tail risks. However, the price of this tail risk insurance does appear to be low relative to that embedded in equity index option markets. Recall that the returns of the G10 currency carry trade portfolios are strongly positively related to the returns of a mechanical S&P 500 index put writing strategy (Table II), and exhibit low to negative excess returns relative to this risk factor. This implies that hedging currency carry trades using equity index options would result in excess returns that are essentially indistinguishable from zero. By contrast, the returns of carry trade strategies hedged in FX options continue to earn positive excess returns (Table III). Caballero and Doyle (2012) similarly argue that FX options provide a cheap form of systematic risk insurance, given the strong correlation between carry trade returns and a strategy which shorts VIX futures. Although crash risk protection indeed appears relatively cheaper in FX option markets than equity index markets, this is perhaps not entirely surprising giving the considerable evidence that equity index options are somewhat expensive relative to their underlying risks (Coval and Shumway (2001), Bakshi and Kapadia (2003), Carr and Wu (2009), Garleanu, et al. (2009), Constantinides, et al. (2013), Jurek and Stafford (2013)).

4.4.2 Transaction costs

The FX option data used in the construction of the returns to hedged currency carry trades are over-the-counter *midquotes*. In practice, traders seeking to execute the hedging strategy would additionally have to pay the bid/ask spread, which would drive down the returns to the hedged strategies, and consequently, increase the estimate of the jump risk premium.

To evaluate the impact of transaction costs on the strategy returns, I apply a simple multiplicative transformation to the implied volatilities, thus increasing the price of all options being purchased. Since bid-ask spreads are typically on the order of $\pm 0.5 - 1\%$, and the mean option-implied volatility is 10%, I apply a volatility multiplier of $1.1x$ to the quoted implied volatilities. Therefore, an option with an implied volatility of $y\%$ is purchased at an implied volatility of $1.1 \cdot y\%$. With this modification, the returns to the 10δ hedged carry trades decline, but remain statistically greater than zero at the 10% significance level (Table V). The corresponding estimates of the jump risk premium increase, and range from 1.3% (t-stat: 2.86) to 1.6% (t-stat: 3.39) *per annum*, accounting for 22% to 31% of the unhedged portfolio return.

A related question, inspired by the hypothesis that *only* jump risks are priced, is what would it have taken – in terms of a shift in option prices (implied volatilities) – for the point estimates of the excess returns to the crash-neutral strategies to equal zero in the historical sample? I find that, in order for this to be the case, the FX option implied volatilities would have had to have been roughly 40% larger that the values observed in the data. For example, with a multiplier of $1.4x$, the excess returns on the hierarchically-hedged, spread-weighted, portfolios are 0.36% (non-dollar-neutral) and -0.49% (dollar-neutral) *per annum*. The corresponding excess returns for the combinatorially hedged portfolios are 0.48% (non-dollar-neutral) and -0.34% (dollar-neutral) *per annum*.

4.4.3 Fixed moneyness hedging

A key feature of foreign exchange markets is the presence of stochastic volatility, and the dramatic rise of realized and option-implied volatilities during the second half of 2008 (Figure 1; bottom panel). Intuitively, fixing the delta of the hedge implies that the probability of observing the option expire in-the-money is being held roughly constant, which requires that the distance between the prevailing forward price and the option strike increase (decrease) with volatility. As a result, the hedging strategy exposes the trade to progressively larger losses as option-implied volatilities increase. By contrast, if investors are focused on drawdowns or are interested in capping the maximum monthly loss, fixed *moneyness* hedging strategies would be more appropriate. These strategies limit the loss to the option premium plus a pre-specified absolute return magnitude, determined by the distance, m, of the option strike from the prevailing forward rate. Of course, as implied volatilities increase options struck at a given moneyness will have a higher delta, and therefore command a larger premium.

To examine the effect of fixed moneyness hedging, I consider strategies which buy options which are 3.5% out-of-the-money relative to the forward rate (Table VI). This level of moneyness is chosen to roughly fall between the mean moneyness of the 10δ and 25δ options used in the preceding analysis. To compute the prices of the FX options at fixed moneyness I interpolate the implied volatility curve using the method of Castagna and Mercurio (2007), and append flat tails beyond the last observed implied volatility quotes. The 3.5% out-of-the-money options generally lie between the observed quotes for the 10δ and 25δ options, such that the return computation depends primarily on values interpolated between actual, observed quotes. When the desired fixed-moneyness option lies outside the range of quotes prices (i.e. has a delta smaller than 10 in absolute value), appending flat tails to the implied volatility may bias the returns of the hedged trades upwards by underestimating the true price of the tail risk insurance. In general, the bias turns out to be empirically negligible, since options which are 3.5% out-of-the-money are only outside the observed range when implied volatilities are extremely low.

The returns to crash-neutral trades hedged at fixed delta of 10δ and 25δ, and at a fixed moneyness 3.5% out-of-the-money, are reported in Table VI. The fixed moneyness hedging scheme selects options with *deltas* ranging from 0 to 42; by contrast, the fixed 10δ (25δ) hedging scheme selects options with *moneyness* ranging from 1.5% to 24.1% (0.7% to 11.2%) out-of-the-money.[15] These wide ranges reflect the significant effects of stochastic volatility on the mapping between the delta of an option and its moneyness. Consistent with intuition, portfolios hedged at fixed moneyness eliminate the risk of severe downside realizations at the expense of greater

[15] Approximately one quarter of the options selected in the fixed-moneyness, hierarchical hedging scheme have a delta less than 10 in absolute value, such that their pricing relies on extrapolated implied volatilities. The average delta of these options is 5.

hedging costs, realizing lower volatility and less extreme returns.

By hedging at a fixed distance from the prevailing forward price the fixed moneyness scheme implicitly attributes the increased price of tail risk insurance during periods of high volatility to jump risk. Consequently, the comparison of mean returns to unhedged currency carry trade portfolios with portfolios hedged at fixed moneyness, suggests a much greater contribution of jump risk premia to the total currency risk premium. These values are generally twice as large as the mean share obtained under the two fixed delta hedging schemes (10δ and 25δ) bracketing the fixed moneyness of 3.5%.[16] These estimates as less compelling, since they fail to control for the time-varying probability of observing extreme return realizations driven simply by variation in the level of exchange rate volatility.

5 Conclusion

The analysis of returns to currency carry trade portfolios, which have been hedged against the risk of crashes using foreign exchange options, suggests a modest role for crash risk premia in rationalizing violations of UIP in developed markets. I find that unhedged, spread-weighted currency carry trade portfolios earn between 4.96% and 5.58% *per annum* (1999:1-2012:6), depending on their net U.S. dollar exposure, and that these returns decline by only 0.20% to 0.50% *per annum*, when hedged with out-of-the-money (10δ) options. The inclusion of conservatively estimated transaction costs increases estimates of the jump risk premium to 1.3-1.6% *per annum*, by increasing the cost of the option hedge and therefore increasing the wedge between the returns of the unhedged and hedged portfolios. The results are robust to imposing constraints of dollar-neutrality, the portfolio rebalancing frequency, as well as, the details of the option hedging scheme, indicating that crash risk premia account for at most one-third of the excess return earned by spread-weighted currency carry trades in G10 currencies. These low estimates contrast starkly with previous evidence reported by Burnside, et al. (2011) and Farhi, et al. (2013), and owe to the improved efficiency of the hedging scheme, based on out-of-the-money cross-rate options.

[16]To assess the effect of the extrapolation scheme on the estimate of the jump risk premium I repeat the above computation, but with implied volatilities which are first extrapolated to 1δ using the method of Castagna and Mercurio (2007), before appending flat tails. The estimates of the jump risk premium increase from 1.42% to 1.44% *per annum* for the dollar-neutral portfolio, and from 1.51% to 1.54% for the non-dollar-neutral portfolio.

A Computing Risk-neutral Moments from FX Options

Breeden and Litzenberger (1978) were the first to show that an asset's entire risk-neutral distribution (i.e. state price density) can be recovered from the prices of a complete set of options on that asset. Following the logic of state-contingent (Arrow-Debreu) pricing, the risk-neutral distribution, $q(S)$, enables one to value arbitrary state contingent payoffs, $H(S)$, via the following pricing equation:

$$p_t = \exp(-y^i_{t,t+\tau} \cdot \tau) \cdot \int_0^\infty H(S_{t+\tau}) \cdot q(S_{t+\tau}) dS_{t+\tau} \tag{A.1}$$

In practice, using the above formula for valuation is difficult since state-contingent claims (or Arrow-Debreu securities) are not traded in real-world capital markets. However, Bakshi and Madan (2000) show that any payoff function with bounded expectation can be spanned by a continuum of out-of-the-money call and put payoffs, which are commonly traded instruments. This implies that the price, p_t, of an asset paying, $H(S_{t+\tau})$, can be conveniently obtained by valuing the relevant replicating portfolio of options. Specifically, if the payoff function is twice-differentiable, the asset's price can be obtained from:

$$\begin{aligned} p_t &= \exp(-y^i_{t,t+\tau} \cdot \tau) \cdot (H(\overline{S}) - \overline{S}) + H_S(\overline{S}) \cdot S_t + \\ &\quad + \int_{\overline{S}}^\infty H_{SS}(K) \cdot \mathcal{C}_t(K,\tau) \cdot dK + \int_0^{\overline{S}} H_{SS}(K) \cdot \mathcal{P}_t(K,\tau) \cdot dK \end{aligned} \tag{A.2}$$

where K are option strike prices, $H_S(\cdot)$ and $H_{SS}(\cdot)$, denote the first and second derivatives of the state-contingent payoff, and $\overline{S}$ is some future value of the underlying, typically taken to be the forward price. Intuitively, this expression states that the payoff $H(S)$ can be synthesized by buying $(H(\overline{S}) - \overline{S})$ units of a riskless bond, $H_S(\overline{S})$ units of the underlying security and a linear combination of puts and calls with positions given by $H_{SS}(K)$.

A.1 Moment swaps

Let $\mu_{k,t}(\tau)$ denote k-th non-central moment of the distribution of the log return at horizon τ under measure $\mathbb{M}^i$:

$$\mu_{i,t} = E_t^{\mathbb{M}^i}\left[\left(\ln \frac{S^{ji}_{t+\tau}}{S^{ji}_t}\right)^k\right] \tag{A.3}$$

Bakshi, Kapadia and Madan (2003) show that the time t price of hypothetical swaps, whose payoff is equal to the consecutive non-central moments ($k = \{2,\ 3,\ 4\}$) of the return can be computed by constructing the appropriate portfolios of puts and calls:[17]

$$V_t(\tau) = \int_{\overline{S}}^\infty \frac{2 \cdot \left(1 - \ln \frac{K}{\overline{S}}\right)}{K^2} \cdot \mathcal{C}_t(K,\tau) \cdot dK + \int_0^{\overline{S}} \frac{2 \cdot \left(1 + \ln \frac{\overline{S}}{K}\right)}{K^2} \cdot \mathcal{P}_t(K,\tau) \cdot dK \tag{A.4}$$

$$W_t(\tau) = \int_{\overline{S}}^\infty \frac{6 \cdot \ln \frac{K}{\overline{S}} - 3 \cdot \left(\ln \frac{K}{\overline{S}}\right)^2}{K^2} \cdot \mathcal{C}_t(K,\tau) \cdot dK - \int_0^{\overline{S}} \frac{6 \cdot \ln \frac{\overline{S}}{K} + 3 \cdot \left(\ln \frac{\overline{S}}{K}\right)^2}{K^2} \cdot \mathcal{P}_t(K,\tau) \cdot dK \tag{A.5}$$

$$X_t(\tau) = \int_{\overline{S}}^\infty \frac{12 \cdot \left(\ln \frac{K}{\overline{S}}\right)^2 - 4 \cdot \left(\ln \frac{K}{\overline{S}}\right)^3}{K^2} \cdot \mathcal{C}_t(K,\tau) \cdot dK + \int_0^{\overline{S}} \frac{12 \cdot \left(\ln \frac{\overline{S}}{K}\right)^2 + 4 \cdot \left(\ln \frac{\overline{S}}{K}\right)^3}{K^2} \cdot \mathcal{P}_t(K,\tau) \cdot dK \tag{A.6}$$

[17] The derivations in Bakshi, et al. (2003) are carried out under the assumption that interest rates are constant over the payoff interval, τ. In this case the derived moments correspond to the risk-neutral measure, $\mathbb{Q}^i$. More generally, when interest rates are time varying, their derivation goes through unaltered but provides moments under the risk-forward measure, $\mathbb{F}^i_\tau$, whose numeraire is the zero-coupon bond maturing τ periods into the future. The risk-forward, $\mathbb{F}^i_\tau$, and risk-neutral, $\mathbb{Q}^i$, measures are trivially identical when interest rates are constant.

where K is the option strike prices, $\mathcal{C}_t(K,\tau)$ and $\mathcal{P}_t(K,\tau)$ are the prices of call and put options struck at K with τ-periods to maturity and $\overline{S}$ is some constant, typically chosen to be either the spot or forward price. Since the above expressions are *prices*, or discounted values, in order to recover the non-central moments I need to adjust for the passage of time. Consequently, the non-central moments are given by: $\mu_{2,t}(\tau) = \exp(y^i_{t,t+\tau}\cdot\tau)\cdot V_t(\tau)$, $\mu_{3,t}(\tau) = \exp(y^i_{t,t+\tau}\cdot\tau)\cdot W_t(\tau)$ and $\mu_{4,t}(\tau) = \exp(y^i_{t,t+\tau}\cdot\tau)\cdot X_t(\tau)$, where $y^i_{t,t+\tau}$ is the risk-free rate of interest corresponding to horizon τ. The risk-neutral variance, skewness, and kurtosis can then be computed by applying their standard definitions:

$$\text{VAR}^{\mathbb{M}^i}_t(\tau) = \mu_{2,t}(\tau) - \mu_{1,t}(\tau)^2 \tag{A.7}$$

$$\text{SKEW}^{\mathbb{M}^i}_t(\tau) = \frac{\mu_{3,t}(\tau) - 3\cdot\mu_{1,t}(\tau)\cdot\mu_{2,t}(\tau) + 2\cdot\mu_{1,t}(\tau)^3}{(\mu_{2,t}(\tau)-\mu_{1,t}(\tau)^2)^{\frac{3}{2}}} \tag{A.8}$$

$$\begin{aligned}\text{KURT}^{\mathbb{M}^i}_t(\tau) &= \frac{\mu_{4,t}(\tau) - 4\cdot\mu_{3,t}\cdot\mu_{1,t}(\tau) + 6\cdot\mu_{2,t}(\tau)\cdot\mu_{1,t}(\tau)^2 - 3\cdot\mu_{1,t}(\tau)^4}{(\mu_{2,t}(\tau)-\mu_{1,t}(\tau)^2)^2}\\ &= 3 + \frac{\mu_{4,t}(\tau) - 4\cdot\mu_{3,t}\cdot\mu_{1,t}(\tau) - 3\cdot\mu_{2,t}(\tau)^2 + 12\cdot\mu_{2,t}(\tau)\cdot\mu_{1,t}(\tau)^2 - 6\cdot\mu_{1,t}(\tau)^4}{(\mu_{2,t}(\tau)-\mu_{1,t}(\tau)^2)^2}\end{aligned} \tag{A.9}$$

where, $\mu_{1,t}(\tau)$, is the mean log return. This quantity can be well approximated by noting that:

$$\begin{aligned}E^{\mathbb{M}^i}_t\left[\exp\left(\ln\frac{S^{ji}_{t+\tau}}{S^{ji}_t}\right)\right] &\approx E^{\mathbb{M}^i}_t\left[1+\left(\ln\frac{S^{ji}_{t+\tau}}{S^{ji}_t}\right)+\frac{1}{2}\cdot\left(\ln\frac{S^{ji}_{t+\tau}}{S^{ji}_t}\right)^2+\frac{1}{6}\cdot\left(\ln\frac{S^{ji}_{t+\tau}}{S^{ji}_t}\right)^3+\frac{1}{24}\cdot\left(\ln\frac{S^{ji}_{t+\tau}}{S^{ji}_t}\right)^4\right]\\ &= 1+\mu_{1,t}(\tau)+\exp(y^i_{t,t+\tau}\cdot\tau)\cdot\left(\frac{V_t(\tau)}{2}+\frac{W_t(\tau)}{6}+\frac{X_t(\tau)}{24}\right)\end{aligned} \tag{A.10}$$

Simultaneously, $E^{\mathbb{M}^i}_t\left[\frac{S^{ji}_{t+\tau}}{S^{ji}_t}\right] = \exp\left(\left(y^i_{t,t+\tau} - r^j_{t,t+\tau}\right)\cdot\tau\right)$, such that:

$$\mu_{1,t}(\tau) \approx \exp\left(\left(y^i_{t,t+\tau} - r^j_{t,t+\tau}\right)\cdot\tau\right) - 1 - \exp\left(y^i_{t,t+\tau}\cdot\tau\right)\cdot\left(\frac{V_t(\tau)}{2}+\frac{W_t(\tau)}{6}+\frac{X_t(\tau)}{24}\right) \tag{A.11}$$

A.2 Interpolation

The formulas for the risk-neutral moments derived by Bakshi, et al. (2003) assume the existence of a continuum of out-of-the-money puts and calls. In reality, of course, the data are available only at a discrete set of strikes spanning a bounded range of strike values, $[K_{min}, K_{max}]$, such that: (a) any implementation of the moment formulas requires interpolation and extrapolating the implied volatility function; and (b) the resulting quantities are only an approximation to the true moments.

Jiang and Tian (2005) investigate these types of approximation errors in the context of computing estimates of the risk-neutral variance from observations of equity index option prices. They conclude that the discreteness of available strikes is not a major issue, and that estimation errors decline to 2.5% (0.5%) of the true volatility when the most deep out-of-the-money options are struck at 1 (1.5) standard deviations away from the forward price. With options struck at two standard deviations away from the forward price, approximation errors essentially disappear completely. Moreover, their results indicate that approximation errors are minimized by interpolating the option implied volatilities within the observed range of strikes, and extrapolating the option implied volatilities below K_{min} and above K_{max} by appending flat tails at the level of the last observed implied volatility. Consistent with intuition, they find that this form of extrapolation is preferred to simply truncating the range of strikes used in the computation.

In the option dataset, the furthest out-of-the-money option quotes correspond to the 10δ puts and calls. Their strikes are roughly 1.4 times the at-the-money implied volatility away from the prevailing forward prices. In order to compute the option-implied moments I: (1) interpolate the implied volatility functions using the *vanna-volga method* (Castagna and Mercurio (2007)), which is the standard approach used by participants in the FX option market; and (2) append flat tails for strikes prices beyond the 10δ threshold. Carr and Wu (2009) follow a similar protocol in their study of variance risk premia in the equity market, and combine linear interpolation between observed implied volatilities with appending flat tails beyond the last observed strikes. The resulting moments turn out to be largely unaffected by the precise details of the *interpolation* scheme. For example, similar results obtain if a standard linear interpolation is used. The choice of the *extrapolation* threshold does have an impact on the magnitudes of the higher moments (skewness / kurtosis). The vanna-volga approximation is essentially quadratic in the log strike, such it violates the technical conditions for the existence of moments under the risk-neutral measure when extrapolated to zero or infinity (Lee (2004)).

The vanna-volga method is based on a static hedging argument, and essentially prices a non-traded option by constructing and pricing a replicating portfolio, which matches all partial derivatives up to second order. In a Black-Scholes world, only first derivatives are matched dynamically, so the replicating delta-neutral portfolio is comprised only of a riskless bond and the underlying. However, in the presence of time-varying volatility, it is necessary to also hedge the *vega* $\left(\frac{\partial C^{BS}}{\partial \sigma}\right)$, as well as, the *volga* $\left(\frac{\partial^2 C^{BS}}{\partial^2 \sigma}\right)$ and *vanna* $\left(\frac{\partial^2 C^{BS}}{\partial \sigma \partial S_t}\right)$. In order to match these three additional moments, the replicating portfolio must now also include an additional three traded options. Consequently, to the extent that at least three FX options are available, the implied volatilities of the remaining options can be obtained by constructing the relevant replicating portfolio, and then inverting its price to obtain the corresponding implied volatility. Castagna and Mercurio (2007) show that the interpolated implied volatility for a τ-period option at strike K obtained from the vanna-volga method is approximately related to the implied volatilities of three other traded option with the same maturity and strikes $K_1 < K_2 < K_3$ through:

$$\tilde{\sigma}_t(K,\tau) \approx \frac{\ln\frac{K_2}{K} \cdot \ln\frac{K_3}{K}}{\ln\frac{K_2}{K_1} \cdot \ln\frac{K_3}{K_1}} \cdot \sigma_t(K_1,\tau) + \frac{\ln\frac{K}{K_1} \cdot \ln\frac{K_3}{K}}{\ln\frac{K_2}{K_1} \cdot \ln\frac{K_3}{K_2}} \cdot \sigma_t(K_2,\tau) + \frac{\ln\frac{K}{K_1} \cdot \ln\frac{K}{K_2}}{\ln\frac{K_3}{K_1} \cdot \ln\frac{K_3}{K_2}} \cdot \sigma_t(K_3,\tau) \tag{A.12}$$

This formula provides a convenient shortcut for carrying out the interpolation and is known to provide very accurate estimates of the implied volatilities whenever K is between K_1 and K_3. In the empirical implementation, interpolated volatilities in the $(10\delta_p,\, 25\delta_p)$ range are based on the $(10\delta_p,\, 25\delta_p,\, ATM)$ option triplet; in the $(25\delta_p,\, 25\delta_c)$ range – on the $(25\delta_p,\, ATM,\, 25\delta_c)$ option triplet; and, in the $(25\delta_c,\, 10\delta_c)$ range – on the $(ATM,\, 25\delta_c,\, 10\delta_c)$. Implied volatilities below $10\delta_p$ and above $10\delta_c$ are set equal to their values at those thresholds, unless otherwise noted.

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Figure 1. Total Returns to G10 Currency Carry Trades. The top panel of this figure illustrates the total return indices for portfolios of G10 currency carry trades over the period from January 1990 to June 2012. The portfolio composition is determined by sorting currencies on the basis of their prevailing 1-month LIBOR rate, and going long (short) currencies with the highest (lowest) interest rates. Portfolios are rebalanced monthly, and allocations to individual currencies are spread-weighted. The graphs plots the returns to dollar-neutral and non-dollar-neutral portfolios. The bottom panel plots the time series of instantaneous volatility for the spread-weighted, non-dollar neutral currency carry trade portfolio. The plot reports values based on an EGARCH(1, 1) model estimated in-sample using daily, historical realized returns (1990:1-2012:6), and a measure of portfolio volatility based on FX option-implied volatilities (1999:1-2012:6). The *FX Option-implied* volatility measure is obtained by reconstructing the portfolio variance-covariance matrix using the full cross-section of 45 G10 cross-rate variance swap quotes.

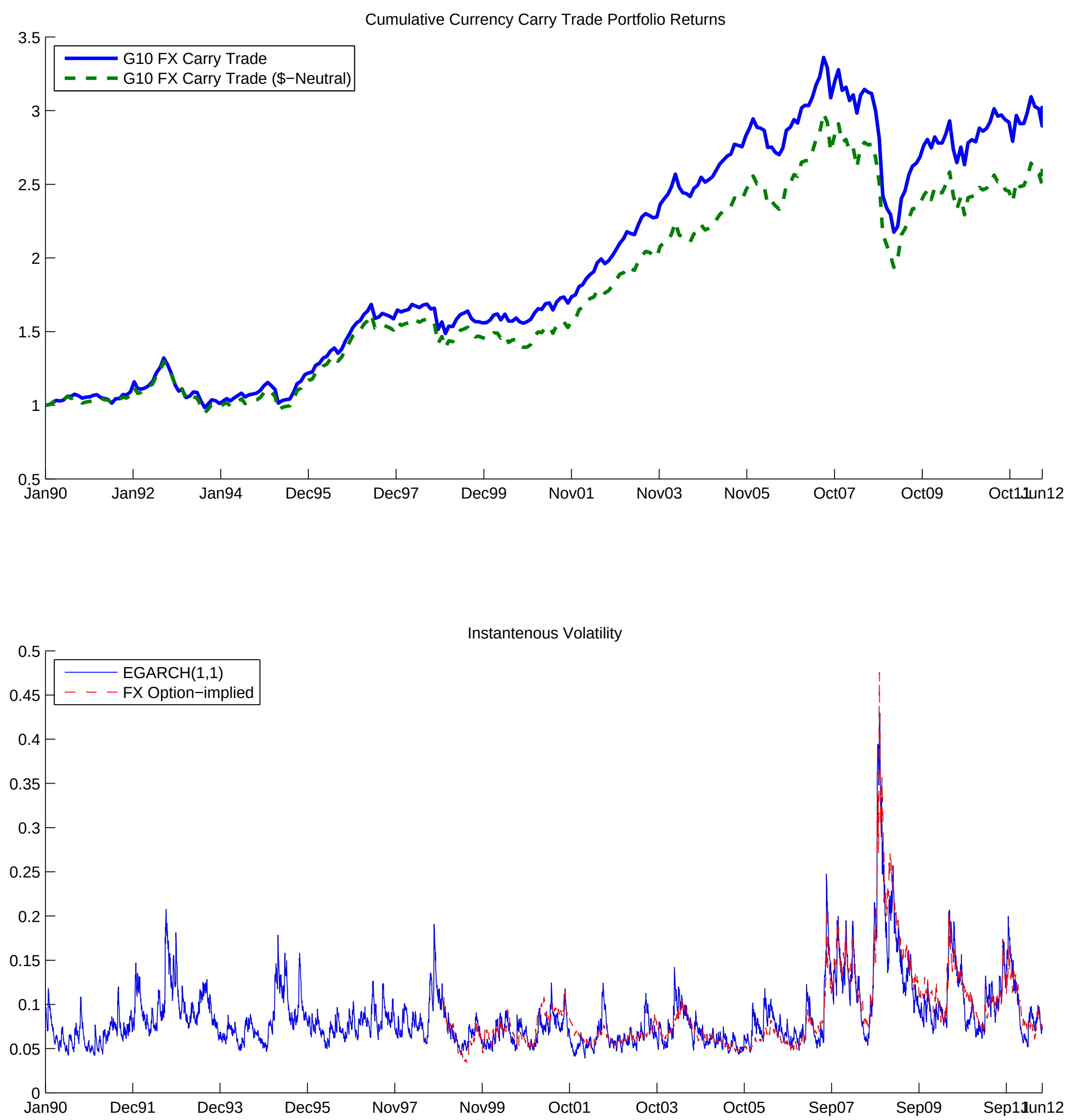

Figure 2. Risk-Neutral Moments and Interest Rate Differentials. The scatter plots depict the relationship between the mean currency pair risk-neutral volatility (left panel) and skewness (right panel), and the mean one-month LIBOR interest rate differential. The risk-neutral moments are computed using the method in Bakshi, et al. (2003), based on implied volatility functions which have been interpolated using the vanna-volga method and extrapolated by appending flat tails below (above) the strike of 10δ put (call). The underlying data are daily and cover the period from January 1999 to June 2012 ($N = 3520$ days).

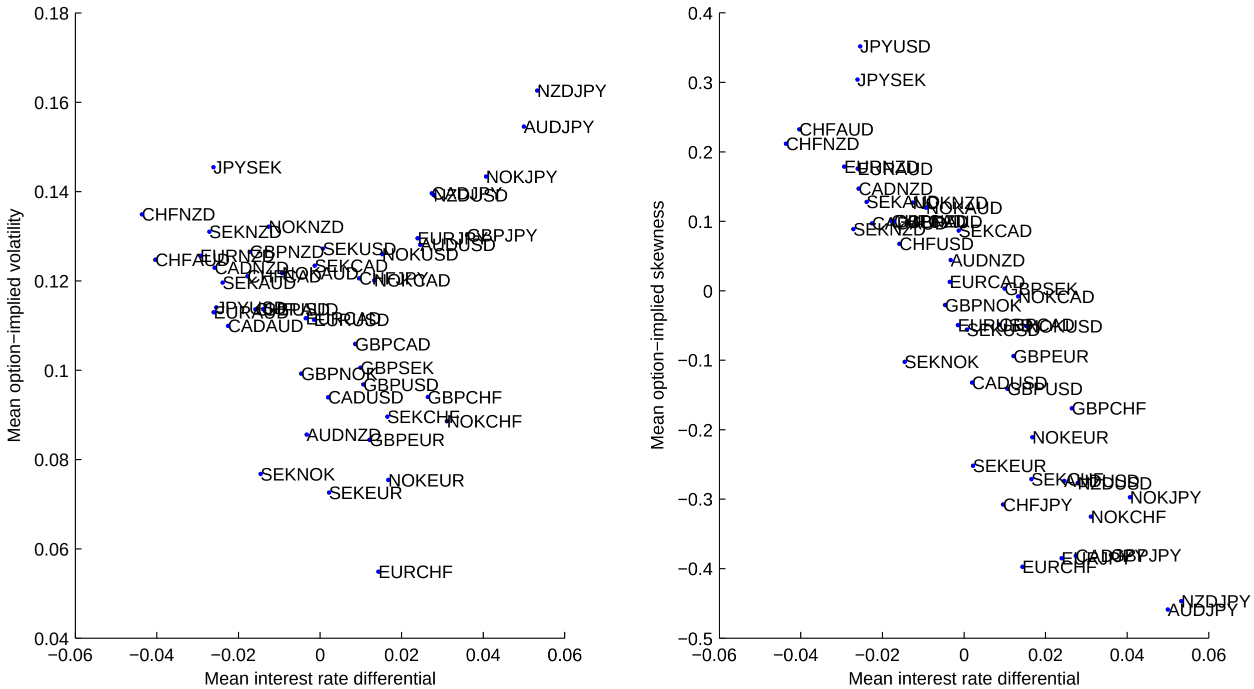

Figure 3. Implied Volatility Functions for X/USD G10 Pairs. The figure illustrates the average implied volatility functions for foreign exchange options on nine G10 currencies versus the U.S. dollar. The implied volatilities have been scaled by the contemporaneous at-the-money implied volatilities to provide a scale-free representation of the skew. The implied volatilities at the five standardized value (10δ put, 25δ put, ATM, 25δ call, 10δ call) are actual observed quotes, and are marked with stars. All other volatilities were obtained by interpolating the data using the vanna-volga method. The dashed red (solid blue) lines correspond to time series means for periods in which the foreign one-month LIBOR rate was at least 1% above (below) the one-month U.S. dollar LIBOR rate. The underlying data are daily and cover the period from January 1999 to June 2012 ($N = 3520$ days).

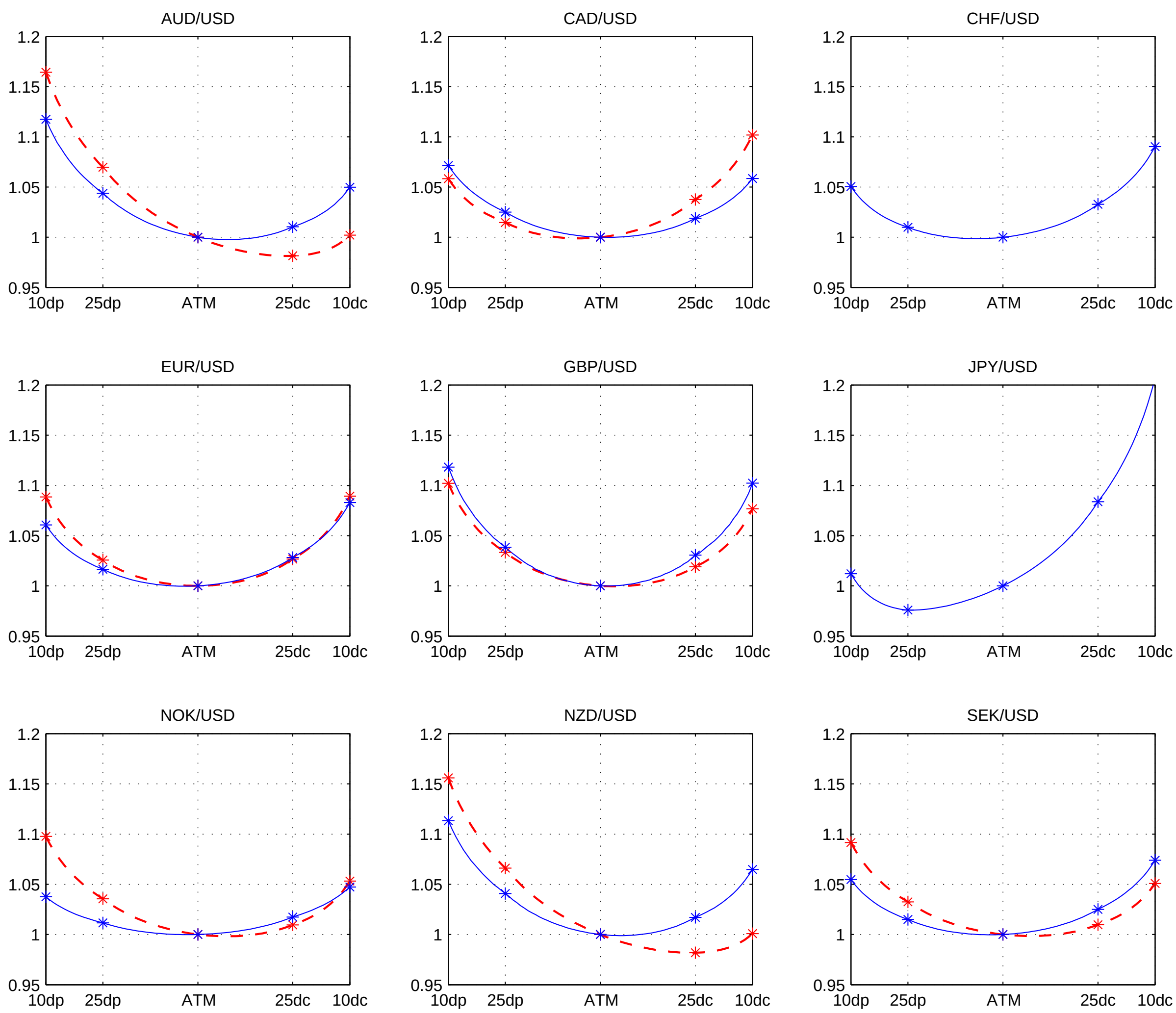

Figure 4. Total Returns to Hedged G10 Currency Carry Trades. This figure plots the total accumulated wealth from investing in the spread-weighted, non-dollar neutral currency carry trade portfolio, under various FX option hedging schemes (top panel). Each of the option hedging schemes utilizes 10δ (out-of-the-money) FX options. Portfolios are rebalanced monthly, and returns are computed for the period from January 1999 to June 2012 (N = 162 months). The bottom panel plots the ratio of the hedged wealth to the unhedged wealth under the three hedging schemes over the same time period.

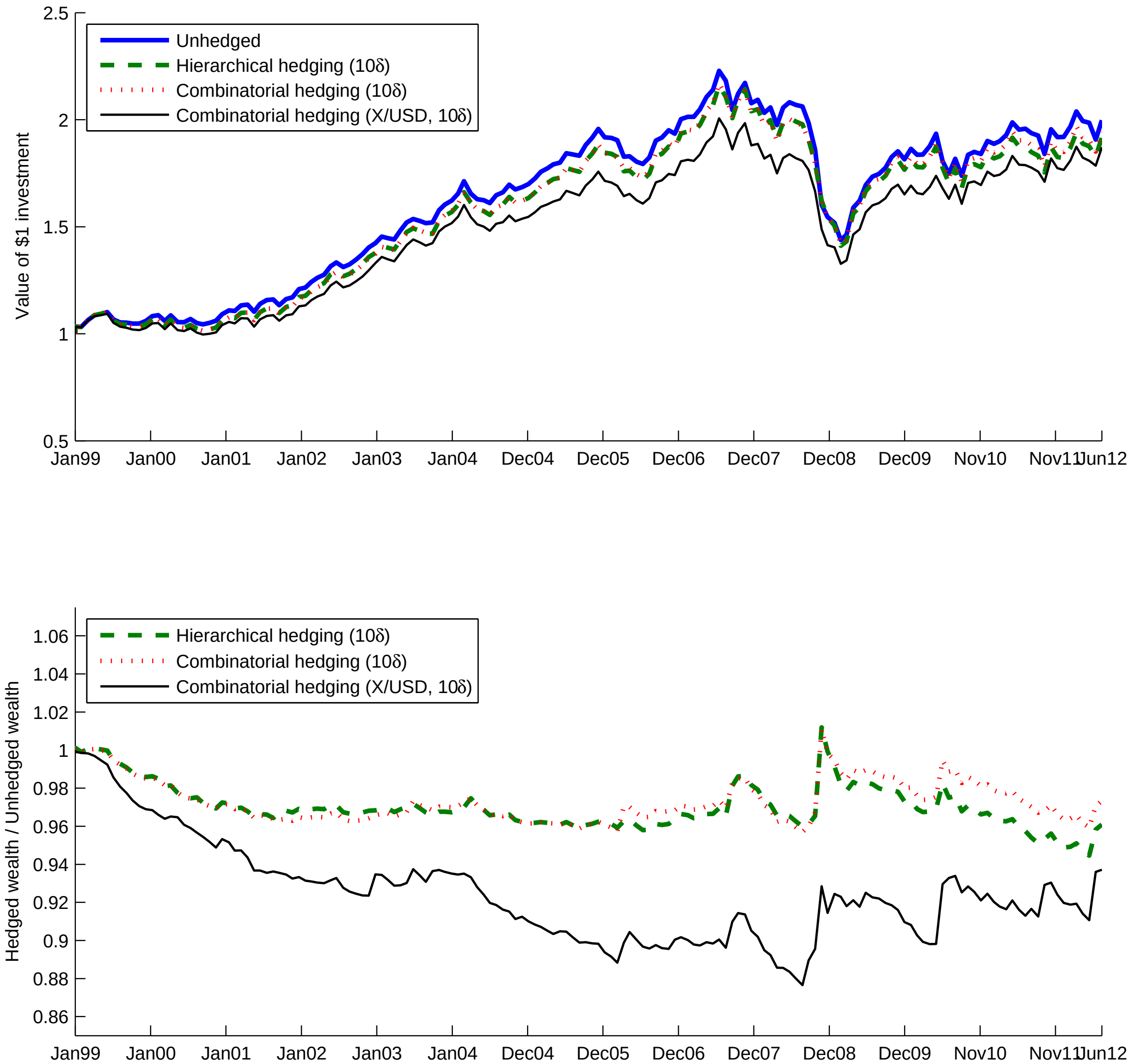

Figure 5. Variance and Skewness Risk Premia in G10 Currencies. This figure displays the mean variance and skewness risk premium for each of the 45 G10 currency pairs as a function of the corresponding mean interest rate differential. The risk premia are computed as the difference between the risk-neutral variance (skewness) and its realized counterpart. Realized moments (variance and skewness) are computed using daily intra-month currency excess returns. Option-implied moments are computed using the method of Bakshi, et al. (2003), and are based on implied volatility functions from one-month options, which have been interpolated using the vanna-volga method, and extrapolated by appending flat tails for strikes below (above) the 10δ put (call). The risk-neutral moments are computed as of the end of month, t, and are then compared with the intra-month realized counterpart in month $t+1$. Currency pairs with risk premia which are statistically distinguishable from zero at the 5% significance level are additionally denoted with red circles. Interest rate differentials are computed on the basis of the one-month LIBOR rates. The data span the period from January 1999 to June 2012 (N = 162 months).

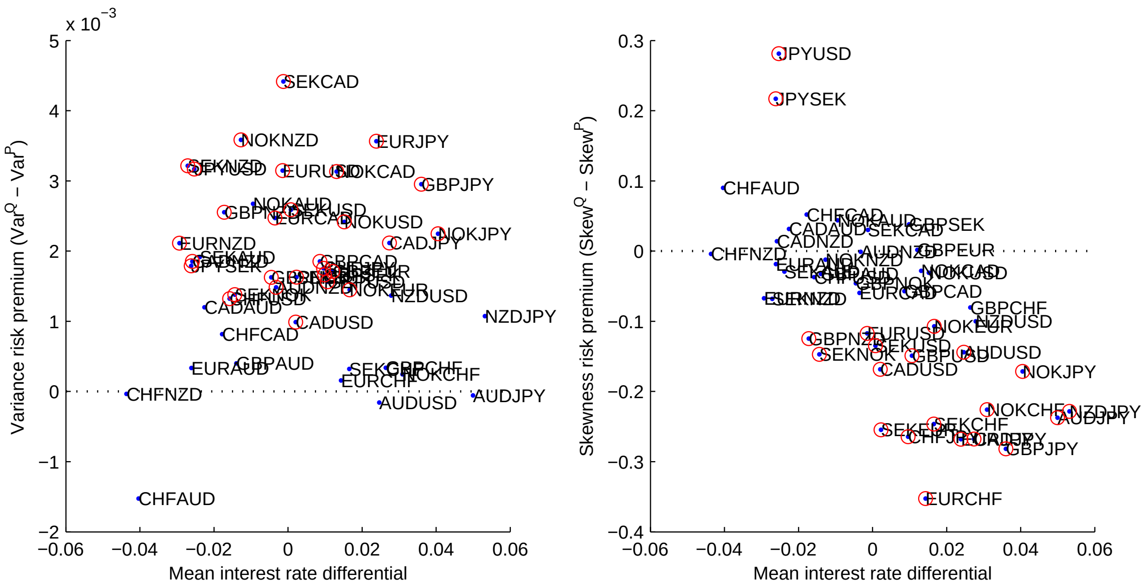

Table I
Returns to Currency Carry Trade Portfolios in G10 Currencies

Panel A reports summary statistics for portfolios of currency carry trades implemented in G10 currencies. The portfolio composition is determined by sorting currencies on the basis of their prevailing 1-month LIBOR rate, and going long (short) currencies with the highest (lowest) interest rates. Portfolios are rebalanced monthly, and allocations to individual currencies are spread-weighted (SPR) or equal-weighted (EQL). The table additionally reports returns to portfolios that have been constrained to be dollar-neutral ($N). Summary statistics are reported over two windows: Jan. 1990-Jun. 2012 (N = 270 months) and Jan. 1999-Jun. 2012 (N = 162 months). Means, volatilities and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *JB* reports the Jarque-Bera test of normality (p-values in parenthesis). *Carry* reports the contribution to the portfolio returns from the interest rate differential between the long and short currencies. *Min* and *Max* report the smallest and largest observed monthly return. Panel B repeats the analysis for standardized portfolio returns (Z-scores), which are obtained by scaling the monthly *log* portfolio returns by an *ex ante* measure of volatility obtained from an EGARCH(1, 1) model estimated in-sample using daily portfolio returns.

Panel A: G10 Carry Trade Returns

	1990:1-2012:6				**1999:1-2012:6**			
	SPR	SPR-$N	EQL	EQL-$N	SPR	SPR-$N	EQL	EQL-$N
Mean	0.0521	0.0454	0.0336	0.0261	0.0558	0.0496	0.0351	0.0282
	[2.62]	[2.27]	[2.39]	[1.85]	[2.19]	[1.92]	[1.96]	[1.63]
Volatility	0.0942	0.0950	0.0667	0.0669	0.0938	0.0951	0.0659	0.0635
Skewness	-1.04	-1.03	-0.71	-0.63	-1.12	-1.07	-1.07	-0.96
Kurtosis	6.08	5.92	4.60	4.30	7.36	7.03	5.58	4.72
Minimum	-0.1383	-0.1394	-0.0836	-0.0743	-0.1383	-0.1394	-0.0836	-0.0743
Maximum	0.0860	0.0824	0.0562	0.0570	0.0860	0.0824	0.0438	0.0382
JB	156.05	143.61	51.72	37.23	162.19	141.02	75.90	44.74
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Carry	0.0532	0.0555	0.0405	0.0430	0.0457	0.0472	0.0331	0.0350
SR	0.55	0.48	0.50	0.39	0.59	0.52	0.53	0.44
N	270	270	270	270	162	162	162	162

Panel A: G10 Carry Trade Returns

	1990:1-2012:6				**1999:1-2012:6**			
	SPR	SPR-$N	EQL	EQL-$N	SPR	SPR-$N	EQL	EQL-$N
Volatility	0.99	1.00	0.99	0.99	1.01	1.00	0.91	0.94
Skewness	-0.91	-0.86	-0.66	-0.61	-0.75	-0.65	-0.92	-0.98
Kurtosis	4.73	4.52	3.57	3.65	3.63	3.55	4.18	4.50
Minimum	-4.17	-3.99	-2.89	-3.44	-3.15	-3.15	-3.34	-3.61
Maximum	2.60	2.20	2.47	2.40	2.20	2.35	2.09	2.10
JB	71.18	59.60	23.18	21.41	17.71	13.38	32.27	40.87
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.01)
N	270	270	270	270	162	162	162	162

Table II
Relation to Equity Market Factors

Panel A reports summary statistics for monthly returns of the Fama-French/Carhart equity factors, and the excess return on the $[Z = -1, L = 2]$ S&P 500 put writing strategy (DRI, downside risk index) from Jurek and Stafford (2013). The put-writing strategy writes short-dated (six-week) equity index put options that are struck one monthly standard deviation out-of-the-money based on the VIX index, and posts capital equal to one-half of the option strike price (leverage factor of two). Means, volatilities and Sharpe ratios are annualized; t-statistics reported in square brackets. Panel B reports results from regressions of the excess return of the spread-weighted G10 carry trade portfolio (non-dollar-neutral and dollar-neutral) on the Fama-French/Carhart factors, and the downside risk index. Regression intercepts are annualized by multiplying by a factor of 12. OLS t-statistics are reported in square brackets below the coefficient estimates. The factor regressions are carried out using two windows: Jan. 1990-Jun. 2012 (N = 270 months) and Jan. 1999-Jun. 2012 (N = 162 months). *Adj.* R^2 reports the adjusted R^2 measure.

Panel A: Risk Factors (1990:1-2012:06)

	RMRF	SMB	HML	UMD	DRI
Mean	0.0620	0.0252	0.0276	0.0719	0.0900
	[1.87]	[1.02]	[1.17]	[1.91]	[6.17]
Volatility	0.1574	0.1178	0.1123	0.1785	0.0692
Skewness	-0.67	0.81	0.09	-1.60	-2.78
SR	0.39	0.21	0.25	0.40	1.30

Panel B: Factor Loadings

	1990:1-2012:06				**1999:1-2012:06**			
	SPR		*SPR*-$N		*SPR*		*SPR*-$N	
Const*12	0.0195	0.0019	0.0130	-0.0032	0.0222	-0.0118	0.0166	-0.0145
	[1.45]	[0.14]	[0.95]	[-0.22]	[1.45]	[-0.74]	[1.10]	[-0.92]
RMRF	0.1673		0.1538		0.2176		0.2010	
	[6.30]		[5.71]		[7.41]		[6.93]	
SMB	0.0143		0.0250		0.0380		0.0356	
	[0.41]		[0.71]		[1.10]		[0.96]	
HML	0.0886		0.0729		0.1159		0.0891	
	[2.39]		[1.94]		[3.10]		[2.41]	
UMD	0.0121		0.0125		0.0252		0.0280	
	[0.54]		[0.55]		[1.12]		[1.26]	
DRI		0.3514		0.3250		0.4856		0.4424
		[6.41]		[5.85]		[8.40]		[7.76]
Adj. R^2	0.1328	0.1297	0.1116	0.1099	0.2968	0.3019	0.2619	0.2690
N	270	270	270	270	162	162	162	162

Table III
Returns to Crash-Neutral Currency Carry Trade Portfolios in G10 Currencies

This table reports summary statistics for returns to spread-weighted portfolios of G10 currency carry trades, which have been crash-hedged using 10δ (out-of-the-money) FX options. The portfolio composition is rebalanced monthly, and is determined by sorting currencies on the basis of their prevailing 1-month LIBOR rate, and going long (short) currencies with high (low) interest rates. Portfolio returns are computed over the period from January 1999 to June 2012 ($N = 162$ months), and are reported separately for non-dollar-neutral portfolios (Panel A) and dollar-neutral portfolios (Panel B). The FX option hedge is established using the full set of 45 G10 cross-rate options (I/J), or only the 9 USD FX options (I/USD). The *hierarchical* hedging scheme uses the smallest possible number of unique currency options by matching the long and short exposures into pairings on the basis of their allocations in the unhedged carry portfolio. The *combinatorial* scheme creates all possible pairings between the long and short currencies, when using the I/J option set; when constrained to I/USD options, the scheme hedges each long and short currency position using the corresponding I/USD FX option. Means, volatilties and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *Minimum* is the smallest observed monthly return. *Difference* reports the difference in the mean return of the unhedged and hedged portfolios (t-statistics in brackets). *Share* (ϕ) captures the share of the jump risk premium in the total currency excess return, and is computed as the ratio of the difference between the unhedged and hedged portfolio returns, and the unhedged portfolio return. Finally, the table reports the average number of FX options in the portfolio at each point in time. *Unique pairs* reports the total number of unique currency pairs considered over the full span of the sample. *Fraction ITM* reports the fraction of FX options which expired in-the-money.

	Panel A: Non-dollar-neutral (SPR)			
	Unhedged	CN(10δ)	CN(10δ)	CN(10δ)
Hedging scheme	None	Hierarchical	Combinatorial	Combinatorial
Option set	-	I/J	I/J	I/USD
Mean	0.0558	0.0527	0.0536	0.0507
	[2.19]	[2.08]	[2.12]	[2.03]
Volatility	0.0938	0.0932	0.0928	0.0917
Skewness	-1.12	-0.42	-0.42	-0.46
Minimum	-0.1383	-0.0967	-0.0993	-0.1065
Difference	-	0.0031	0.0022	0.0051
	-	[0.70]	[0.50]	[0.89]
Share (ϕ)	-	0.0553	0.0389	0.0912
Avg. # pairs	-	9	25	9
Unique pairs	-	37	44	9
Fraction ITM	-	0.0624	0.0617	0.0741
N	162	162	162	162

	Panel B: Dollar-neutral (SPR-$N)			
	Unhedged	CN(10δ)	CN(10δ)	CN(10δ)
Hedging scheme	None	Hierarchical	Combinatorial	Combinatorial
Option set	-	I/J	I/J	I/USD
Mean	0.0496	0.0445	0.0457	0.0426
	[1.92]	[1.72]	[1.78]	[1.68]
Volatility	0.0951	0.0951	0.0945	0.0929
Skewness	-1.07	-0.38	-0.40	-0.47
Minimum	-0.1394	-0.0959	-0.0998	-0.1082
Difference	-	0.0051	0.0039	0.0069
	-	[1.12]	[0.88]	[1.16]
Share (ϕ)	-	0.1022	0.0779	0.1401
Avg. # pairs	-	8	20	9
Unique pairs	-	28	35	9
Fraction ITM	-	0.0610	0.0599	0.0741
N	162	162	162	162

Table IV
FX Variance and Skewness Risk Premia

This table examines the dynamics of realized ($\mathbb{P}$) and option-implied ($\mathbb{Q}$) moments of currency returns, as well as, their associated risk premia, using panel regressions. Realized moments (variance and skewness) are computed using daily intra-month currency excess returns. The notation, $M^{\mathbb{P}}_{t:t+1}$, indicates the moment was computed using the realized intra-month returns starting at the end of month t, through the end of month $t+1$. Option-implied moments are computed using the method of Bakshi, et al. (2003), and are based on implied volatility functions, which have been interpolated using the vanna-volga method, and extrapolated by appending flat tails for strikes below (above) the 10δ put (call). Option-implied moments, $M^{\mathbb{Q}}_t$, are computed as of the last day of month t. $xs^{ji}_{t-1:t}$ is the (lagged) log currency excess return for currency pair J/I computed from the end of month $t-1$, through the end of month t. $y^j_t - y^i_t$ is the one-month LIBOR differential between countries J and I, computed as of the end of month t. The unit of observation is a currency pair/month ($N = 45 \cdot 160 = 7200$), and the panel regression are carried out with currency pair fixed effects (coefficients not reported). The table reports coefficient estimates and the associated t-statistics (reported in square brackets) based on robust standard errors, which have been adjusted for within time-period cross-sectional correlation, as well as, time-series autocorrelation and cross-correlations applying the methodology of Thompson (2011) with three monthly lags. $Adj. R^2$ is the regression adjusted R^2; $Adj. R^2\,[NFE]$ is the regression adjusted R^2 reported net of the explanatory power of the fixed effects.

	$\text{Var}^{\mathbb{P}}_{t:t+1}$	$\text{Var}^{\mathbb{Q}}_{t}$	$\text{Var}^{\mathbb{Q}}_{t} - \text{Var}^{\mathbb{P}}_{t:t+1}$	$\text{Skew}^{\mathbb{P}}_{t:t+1}$	$\text{Skew}^{\mathbb{Q}}_{t}$	$\text{Skew}^{\mathbb{Q}}_{t} - \text{Skew}^{\mathbb{P}}_{t:t+1}$
$xs^{ji}_{t-1:t}$	-0.07	-0.07	-0.00	-1.77	1.89	4.20
	[-2.24]	[-1.56]	[-0.20]	[-3.59]	[11.66]	[7.23]
$y^j_t - y^i_t$	0.05	0.03	-0.02	-3.90	-0.45	2.30
	[1.46]	[1.25]	[-0.79]	[-4.27]	[-2.05]	[2.34]
$\text{Var}^{P}_{t-1:t}$	0.25					
	[2.69]					
Var^{Q}_{t-1}		0.67				
		[5.01]				
$\text{Var}^{Q}_{t-1} - \text{Var}^{P}_{t-1:t}$			-0.04			
			[-0.19]			
$\text{Skew}^{P}_{t-1:t}$				-0.01		
				[-0.14]		
Skew^{Q}_{t-1}					0.75	
					[31.89]	
$\text{Skew}^{Q}_{t-1} - \text{Var}^{P}_{t-1:t}$						0.13
						[4.71]
FX pair FE	Y	Y	Y	Y	Y	Y
Adj. R^2	0.13	0.52	0.00	0.05	0.81	0.09
Adj. $R^2[NFE]$	0.07	0.47	0.00	0.02	0.64	0.06
N	7200	7200	7200	7200	7200	7200

Table V
Returns to Crash-Neutral Currency Carry Trade Portfolios in G10 Currencies: Inclusion of transaction costs

This table reports summary statistics for returns to spread-weighted portfolios of G10 currency carry trades, which have been crash-hedged using 10δ (out-of-the-money) FX options. In order to incorporate the effects of option transaction costs the implied volatilities are multiplied by a factor of 1.1x, such that an option with a quoted implied volatility of 10% is purchased at an implied volatility of 11%. The portfolio composition is rebalanced monthly, and is determined by sorting currencies on the basis of their prevailing 1-month LIBOR rate, and going long (short) currencies with high (low) interest rates. Portfolio returns are computed over the period from January 1999 to June 2012 ($N = 162$ months), and are reported separately for non-dollar-neutral portfolios and dollar-neutral portfolios. The FX option hedge is established using the full set of 45 G10 cross-rate options (I/J). The *hierarchical* hedging scheme uses the smallest possible number of unique currency options by matching the long and short exposures into pairings on the basis of their allocations in the unhedged carry portfolio. The *combinatorial* scheme creates all possible pairings between the long and short currencies, when using the I/J option set; when constrained to I/USD options, the scheme hedges each long and short currency position using the corresponding I/USD FX option. Means, volatilties and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *Minimum* is the smallest observed monthly return. *Difference* reports the difference in the mean return of the unhedged and hedged portfolios (t-statistics in brackets). *Share* (ϕ) captures the share of the jump risk premium in the total currency excess return, and is computed as the ratio of the difference between the unhedged and hedged portfolio returns, and the unhedged portfolio return. Finally, the table reports the average number of FX options in the portfolio at each point in time. *Unique pairs* reports the total number of unique currency pairs considered over the full span of the sample. *Fraction ITM* reports the fraction of FX options which expired in-the-money.

	Non-dollar-neutral (SPR)		**Dollar-neutral (SPR-$N)**	
	CN(10δ)	CN(10δ)	CN(10δ)	CN(10δ)
Hedging scheme	Hierarchical	Combinatorial	Hierarchical	Combinatorial
Option set	I/J	I/J	I/J	I/J
Mean	0.0423	0.0432	0.0340	0.0353
	[1.66]	[1.71]	[1.31]	[1.27]
Volatility	0.0934	0.0929	0.0953	0.0947
Skewness	-0.45	-0.45	-0.41	-0.42
Minimum	-0.0984	-0.1009	-0.0976	-0.1014
Difference	0.0135	0.0126	0.0156	0.0143
	[3.02]	[2.86]	[3.39]	[3.22]
Share (ϕ)	0.2425	0.2251	0.3143	0.2885
Avg. # pairs	9	25	8	20
Unique pairs	37	44	28	35
Fraction ITM	0.0624	0.0617	0.0610	0.0599
N	162	162	162	162

Table VI
Returns to the Crash-Neutral Currency Carry Trade Portfolios in G10 Currencies: Fixed moneyness hedging

This table reports summary statistics for returns to the *crash-neutral* G10 currency carry trade portfolios in G10 currencies. The portfolio composition is determined by sorting currencies on the basis of their prevailing 1-month LIBOR rate, and going long (short) currencies with high (low) interest rates. The composition of the portfolio is rebalanced monthly, and the allocations to individual currencies are spread-weighted. The returns to the carry trade portfolios are reported unhedged, hedged at 10-delta (CN(10δ)), 25-delta (CN(25δ)) and with options that are 3.5% out-of-the-money. In all cases, the FX option hedge is establishing using the smallest possible number of unique currency options by matching the long and short exposures into pairings on the basis of their allocations in unhedged carry portfolio (hierarchical hedging). The table reports the average/maximum/minimum of the option deltas, δ, used in hedging overlay, as well as, the corresponding statistics for the absolute distance of their strike to the forward rate ($m = \frac{F_t - K_{t,p}}{F_t}$). The prices of options at fixed moneyness are computed on the basis of implied volatility functions, which have been interpolated using the the vanna-volga method, and extrapolated by appending flat tails for strikes below (above) the 10δ put (call). Monthly returns are computed over the period from January 1999 to June 2012, with and without imposing dollar-neutrality. Means, volatilties and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *Minimum* is the smallest observed monthly return. *Difference* reports the difference in the mean return of the unhedged and hedged portfolios (t-statistics in brackets). *Share* (ϕ) captures the share of the jump risk premium in the total currency excess return, and is computed as the ratio of the difference between the unhedged and hedged portfolio returns, and the unhedged portfolio return.

	Non-dollar-neutral (SPR)				**Dollar-neutral (SPR-$N)**			
	Unhedged	CN(10δ)	CN(25δ)	CN(3.5% OTM)	Unhedged	CN(10δ)	CN(25δ)	CN(3.5% OTM)
Avg. δ	-	0.10	0.25	0.14	-	0.10	0.25	0.14
Min. δ	-	0.10	0.25	0.00	-	0.10	0.25	0.00
Max. δ	-	0.10	0.25	0.42	-	0.10	0.25	0.42
Avg. m	-	4.7%	2.3%	3.5%	-	4.7%	2.3%	3.5%
Min. m	-	1.5%	0.7%	3.5%	-	1.5%	0.7%	3.5%
Max. m	-	24.1%	11.2%	3.5%	-	24.1%	11.2%	3.5%
Mean	0.0558	0.0524	0.0503	0.0416	0.0496	0.0441	0.0415	0.0344
	[2.19]	[2.07]	[1.95]	[2.09]	[1.92]	[1.70]	[1.58]	[1.69]
Volatility	0.0938	0.0931	0.0945	0.0733	0.0951	0.0950	0.0964	0.0746
Skewness	-1.13	-0.42	0.00	-0.07	-1.08	-0.39	0.00	-0.06
Minimum	-0.1383	-0.0962	-0.0765	-0.0539	-0.1394	-0.0956	-0.0772	-0.0547
Difference	-	0.0034	0.0055	0.0142	-	0.0055	0.0081	0.0151
	-	[0.77]	[0.60]	[1.45]	-	[1.21]	[0.88]	[1.55]
Share	-	0.0617	0.0989	0.2540	-	0.1109	0.1636	0.3055
N	162	162	162	162	162	162	162	162

Table A.I
Returns to Shorting Local Currency Against G10

This table reports summary statistics for returns to the shorting each currency in the G10 against an equal-weighted basket of the remaining nine currencies. Returns are reported over two windows: Jan. 1990-Jun. 2012 (Panel A; N = 270 months) and Jan. 1999-Jun. 2012 (Panel B; N = 162 months). Means, volatilties and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *JB* reports the Jarque-Bera test of normality (p-values in parentheses). The bottom part of each panel reports summary statistics for the corresponding standardized portfolio returns (Z-scores), which are obtained by scaling the monthly *log* portfolio returns by an *ex ante* measure of volatility obtained from an EGARCH(1, 1) model estimated in-sample using daily portfolio returns.

Panel A: Short Local (1990-2012)

		AUD	CAD	CHF	EUR	GBP	JPY	NOK	NZD	SEK	USD
Returns	Mean	-0.0148	0.0104	0.0122	0.0152	0.0037	0.0240	-0.0029	-0.0237	0.0121	0.0231
		[-0.77]	[0.63]	[0.76]	[1.27]	[0.23]	[0.99]	[-0.20]	[-1.27]	[0.78]	[1.36]
	Volatility	0.0916	0.0776	0.0756	0.0565	0.0746	0.1145	0.0679	0.0886	0.0739	0.0807
	Skewness	0.59	0.10	-0.41	0.07	1.22	-0.74	0.48	0.58	1.17	-0.21
	Kurtosis	3.66	3.18	4.29	3.70	8.19	5.67	3.94	5.24	10.02	3.93
	JB	20.37	0.82	26.16	5.72	370.64	104.48	20.06	71.51	616.26	11.68
		(0.00)	(0.66)	(0.00)	(0.05)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)
Z-scores	Volatility	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	1.02	0.99
	Skewness	0.45	0.00	-0.41	-0.12	0.88	-0.73	0.52	0.52	0.88	-0.39
	Kurtosis	2.91	3.10	3.61	3.84	6.34	5.03	4.04	4.18	8.87	3.78
	JB	9.09	0.11	11.90	8.50	160.86	70.02	24.12	27.92	422.87	13.86
		(0.02)	(0.95)	(0.01)	(0.02)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)

Panel B: Short Local (1999-2012)

		AUD	CAD	CHF	EUR	GBP	JPY	NOK	NZD	SEK	USD
Returns	Mean	-0.0384	-0.0056	0.0172	0.0244	0.0229	0.0338	-0.0076	-0.0335	0.0157	0.0312
		[-1.62]	[-0.27]	[0.86]	[1.64]	[1.19]	[1.07]	[-0.40]	[-1.26]	[0.89]	[1.29]
	Volatility	0.0873	0.0776	0.0733	0.0545	0.0706	0.1166	0.0698	0.0978	0.0652	0.0890
	Skewness	0.90	0.45	-0.79	-0.17	1.47	-0.76	0.45	0.67	-0.08	-0.17
	Kurtosis	4.72	3.17	5.68	3.94	9.68	6.00	4.02	5.17	3.49	3.72
	JB	41.77	5.63	65.46	6.67	359.43	76.29	12.53	43.62	1.82	4.24
		(0.00)	(0.05)	(0.00)	(0.04)	(0.00)	(0.00)	(0.01)	(0.00)	(0.34)	(0.09)
Z-scores	Volatility	1.00	1.00	1.02	1.01	0.98	0.99	1.00	1.00	1.02	1.00
	Skewness	0.61	0.36	-0.78	-0.51	0.98	-0.52	0.53	0.65	-0.14	-0.18
	Kurtosis	3.17	2.90	4.33	4.21	5.93	3.89	4.14	4.06	2.96	3.51
	JB	10.26	3.57	28.32	17.00	83.65	12.74	16.40	19.08	0.56	2.68
		(0.01)	(0.12)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.76)	(0.20)

Table A.II
Returns to Currency Carry Trade Portfolios in G10 Currencies Sorted Relative to USD LIBOR

Panel A reports summary statistics for portfolios of currency carry trades implemented in G10 currencies. The portfolio composition is determined by sorting currencies on the basis of their prevailing 1-month LIBOR rate, and going long (short) currencies whose interest rates are above (below) the U.S. dollar short rate. Portfolios are rebalanced monthly, and allocations to individual currencies are spread-weighted (SPR) or equal-weighted (EQL). The table additionally reports returns to portfolios that have been constrained to be dollar-neutral ($N). Note that dollar-neutral portfolios cannot be formed in months in which the U.S. dollar has the highest (or lowest) interest rate. Summary statistics are reported over two windows: Jan. 1990-Jun. 2012 (N = 270 months) and Jan. 1999-Jun. 2012 (N = 162 months). Means, volatilities and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *JB* reports the Jarque-Bera test of normality (p-values in parentheses). *Carry* reports the contribution to the portfolio returns from the interest rate differential between the long and short currencies. *Min* and *Max* report the smallest and largest observed monthly return. Panel B repeats the analysis for standardized portfolio returns (Z-scores), which are obtained by scaling the monthly *log* portfolio returns by an *ex ante* measure of volatility obtained from an EGARCH(1, 1) model estimated in-sample using daily portfolio returns.

Panel A: G10 Carry Trade Returns

	1990:1-2012:6				**1999:1-2012:6**			
	SPR	SPR-$N	EQL	EQL-$N	SPR	SPR-$N	EQL	EQL-$N
Mean	0.0572	0.0488	0.0350	0.0279	0.0640	0.0374	0.0309	0.0150
	[3.15]	[2.35]	[2.70]	[1.59]	[2.51]	[1.36]	[1.75]	[0.65]
Volatility	0.0860	0.0984	0.0615	0.0831	0.0936	0.1015	0.0649	0.0851
Skewness	-0.69	-1.47	-1.06	-1.20	-0.61	-1.61	-1.01	-1.38
Kurtosis	5.99	8.92	7.26	7.60	6.04	9.89	7.66	8.51
Minimum	-0.1089	-0.1696	-0.0959	-0.1362	-0.1089	-0.1696	-0.0959	-0.1362
Maximum	0.0844	0.0651	0.0527	0.0588	0.0844	0.0651	0.0527	0.0539
JB	122.53	425.13	254.72	262.27	72.45	382.41	174.17	251.61
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Carry	0.0340	0.0477	0.0225	0.0337	0.0299	0.0438	0.0184	0.0306
SR	0.67	0.50	0.57	0.34	0.68	0.37	0.48	0.18
N	270	234	270	234	162	159	162	159

Panel A: G10 Carry Trade Returns

	1990:1-2012:6				**1999:1-2012:6**			
	SPR	SPR-$N	EQL	EQL-$N	SPR	SPR-$N	EQL	EQL-$N
Volatility	0.94	1.04	0.94	0.98	0.97	0.99	0.94	0.97
Skewness	-1.11	-6.16	-1.05	0.71	-1.02	-0.71	-0.89	-0.85
Kurtosis	5.67	91.14	5.45	35.47	5.55	4.13	4.97	4.39
Minimum	-4.20	-12.75	-3.80	-7.12	-4.01	-3.41	-3.55	-3.62
Maximum	2.10	6.71	2.26	8.78	2.36	2.70	2.21	2.02
JB	136.00	$89.1 \cdot 10^3$	116.73	$11.8 \cdot 10^3$	71.82	22.17	47.56	32.48
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
N	270	234	270	234	162	159	162	159

Table A.III
Returns to Crash-Neutral Currency Carry Trade Portfolios in G10 Currencies:
Spread-weighted portfolios hedged with 25δ options

This table reports summary statistics for returns to spread-weighted portfolios of G10 currency carry trades, which have been crash-hedged using 25δ FX options. The portfolio composition is rebalanced monthly, and is determined by sorting currencies on the basis of their prevailing 1-month LIBOR rate, and going long (short) currencies with high (low) interest rates. Portfolio returns are computed over the period from January 1999 to June 2012 ($N = 162$ months), and are reported separately for non-dollar-neutral portfolios (Panel A) and dollar-neutral portfolios (Panel B). The FX option hedge is established using the full set of 45 G10 cross-rate options (I/J), or only the 9 USD FX options (I/USD). The *hierarchical* hedging scheme uses the smallest possible number of unique currency options by matching the long and short exposures into pairings on the basis of their allocations in the unhedged carry portfolio. The *combinatorial* scheme creates all possible pairings between the long and short currencies, when using the I/J option set; when constrained to I/USD options, the scheme hedges each long and short currency position using the corresponding I/USD FX option. Means, volatilties and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *Minimum* is the smallest observed monthly return. *Difference* reports the difference in the mean return of the unhedged and hedged portfolios (t-statistics in square brackets). *Share* (ϕ) captures the share of the jump risk premium in the total currency excess return, and is computed as the ratio of the difference between the unhedged and hedged portfolio returns, and the unhedged portfolio return. Finally, the table reports the average number of FX options in the portfolio at each point in time. *Unique pairs* reports the total number of unique currency pairs considered over the full span of the sample. *Fraction ITM* reports the fraction of FX options which expired in-the-money.

	Panel A: Non-dollar-neutral (SPR)			
	Unhedged	CN(25δ)	CN(25δ)	CN(25δ)
Hedging scheme	None	Hierarchical	Combinatorial	Combinatorial
Option set	-	I/J	I/J	I/USD
Mean	0.0558	0.0508	0.0522	0.0476
	[2.19]	[1.97]	[2.05]	[1.81]
Volatility	0.0938	0.0948	0.0935	0.0967
Skewness	-1.12	0.01	0.05	0.04
Minimum	-0.1383	-0.0757	-0.0752	-0.0840
Difference	-	0.0050	0.0036	0.0082
	-	[0.55]	[0.43]	[0.62]
Share (ϕ)	-	0.0899	0.0649	0.1474
Avg. # pairs	-	9	25	9
Unique pairs	-	37	44	9
Fraction ITM	-	0.1879	0.1832	0.2126
N	162	162	162	162

	Panel B: Dollar-neutral (SPR-$N)			
	Unhedged	CN(25δ)	CN(25δ)	CN(25δ)
Hedging scheme	None	Hierarchical	Combinatorial	Combinatorial
Option set	-	I/J	I/J	I/USD
Mean	0.0496	0.0421	0.0437	0.0387
	[1.92]	[1.60]	[1.69]	[1.45]
Volatility	0.0951	0.0968	0.0945	0.0982
Skewness	-1.07	0.01	0.05	-0.06
Minimum	-0.1394	-0.0767	-0.0755	-0.0864
Difference	-	0.0075	0.0058	0.0108
	-	[0.81]	[0.57]	[0.77]
Share (ϕ)	-	0.1507	0.1179	0.2186
Avg. # pairs	-	8	20	9
Unique pairs	-	28	35	9
Fraction ITM	-	0.1906	0.1861	0.2126
N	162	162	162	162

Table A.IV
Returns to Crash-Neutral Currency Carry Trade Portfolios in G10 Currencies: Spread-weighted portfolios hedged with 50δ (at-the-money) options

This table reports summary statistics for returns to spread-weighted portfolios of G10 currency carry trades, which have been crash-hedged using 50δ (at-the-money) FX options. The portfolio composition is rebalanced monthly, and is determined by sorting currencies on the basis of their prevailing 1-month LIBOR rate, and going long (short) currencies with high (low) interest rates. Portfolio returns are computed over the period from January 1999 to June 2012 ($N = 162$ months), and are reported separately for non-dollar-neutral portfolios (Panel A) and dollar-neutral portfolios (Panel B). The FX option hedge is established using the full set of 45 G10 cross-rate options (I/J), or only the 9 USD FX options (I/USD). The *hierarchical* hedging scheme uses the smallest possible number of unique currency options by matching the long and short exposures into pairings on the basis of their allocations in the unhedged carry portfolio. The *combinatorial* scheme creates all possible pairings between the long and short currencies, when using the I/J option set; when constrained to I/USD options, the scheme hedges each long and short currency position using the corresponding I/USD FX option. Means, volatilties and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *Minimum* is the smallest observed monthly return. *Difference* reports the difference in the mean return of the unhedged and hedged portfolios (t-statistics in square brackets). *Share* (ϕ) captures the share of the jump risk premium in the total currency excess return, and is computed as the ratio of the difference between the unhedged and hedged portfolio returns, and the unhedged portfolio return. Finally, the table reports the average number of FX options in the portfolio at each point in time. *Unique pairs* reports the total number of unique currency pairs considered over the full span of the sample. *Fraction ITM* reports the fraction of FX options which expired in-the-money.

	Panel A: Non-dollar-neutral (SPR)			
	Unhedged	CN(50δ)	CN(50δ)	CN(50δ)
Hedging scheme	None	Hierarchical	Combinatorial	Combinatorial
Option set	-	I/J	I/J	I/USD
Mean	0.0558	0.0430	0.0436	0.0381
	[2.19]	[1.58]	[1.64]	[1.16]
Volatility	0.0938	0.0997	0.0979	0.1208
Skewness	-1.12	0.72	0.69	0.67
Minimum	-0.1383	-0.0776	-0.0863	-0.1019
Difference	-	0.0128	0.0122	0.0177
	-	[0.88]	[0.86]	[0.70]
Share (ϕ)	-	0.2302	0.2182	0.3171
Avg. # pairs	-	9	25	9
Unique pairs	-	37	44	9
Fraction ITM	-	0.4294	0.4254	0.4698
N	162	162	162	162

	Panel B: Dollar-neutral (SPR-$N)			
	Unhedged	CN(50δ)	CN(50δ)	CN(50δ)
Hedging scheme	None	Hierarchical	Combinatorial	Combinatorial
Option set	-	I/J	I/J	I/USD
Mean	0.0496	0.0323	0.0337	0.0290
	[1.92]	[1.16]	[1.24]	[0.86]
Volatility	0.0951	0.1022	0.0997	0.1240
Skewness	-1.07	0.67	0.70	0.55
Minimum	-0.1394	-0.0853	-0.0883	-0.1077
Difference	-	0.0172	0.0158	0.0205
	-	[1.14]	[1.10]	[0.76]
Share (ϕ)	-	0.3476	0.3195	0.4145
Avg. # pairs	-	8	20	9
Unique pairs	-	28	35	9
Fraction ITM	-	0.4367	0.4302	0.4698
N	162	162	162	162

Table A.V
Returns to Crash-Neutral Currency Carry Trade Portfolios in G10 Currencies: Equal-weighted portfolios hedged with 10δ (out-of-the-money) options

This table reports summary statistics for returns to *equal-weighted* portfolios of G10 currency carry trades, which have been crash-hedged using 10δ (out-of-the-money) FX options. The portfolio composition is rebalanced monthly, and is determined by sorting currencies on the basis of their prevailing 1-month LIBOR rate, and going long (short) currencies with high (low) interest rates. Portfolio returns are computed over the period from January 1999 to June 2012 (N = 162 months), and are reported separately for non-dollar-neutral portfolios (Panel A) and dollar-neutral portfolios (Panel B). The FX option hedge is established using the full set of 45 G10 cross-rate options (I/J), or only the 9 USD FX options (I/USD). The *hierarchical* hedging scheme uses the smallest possible number of unique currency options by matching the long and short exposures into pairings on the basis of their allocations in the unhedged carry portfolio. The *combinatorial* scheme creates all possible pairings between the long and short currencies, when using the I/J option set; when constrained to I/USD options, the scheme hedges each long and short currency position using the corresponding I/USD FX option. Means, volatilties and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *Minimum* is the smallest observed monthly return. *Difference* reports the difference in the mean return of the unhedged and hedged portfolios (t-statistics in square brackets). *Share* (ϕ) captures the share of the jump risk premium in the total currency excess return, and is computed as the ratio of the difference between the unhedged and hedged portfolio returns, and the unhedged portfolio return. Finally, the table reports the average number of FX options in the portfolio at each point in time. *Unique pairs* reports the total number of unique currency pairs considered over the full span of the sample. *Fraction ITM* reports the fraction of FX options which expired in-the-money.

	Panel A: Non-dollar-neutral (EQL)			
	Unhedged	CN(10δ)	CN(10δ)	CN(10δ)
Hedging scheme	None	Hierarchical	Combinatorial	Combinatorial
Option set	-	I/J	I/J	I/USD
Mean	0.0351	0.0309	0.0313	0.0297
	[1.96]	[1.73]	[1.77]	[1.69]
Volatility	0.0659	0.0655	0.0650	0.0644
Skewness	-1.07	-0.71	-0.61	0.06
Minimum	-0.0836	-0.0693	-0.0634	-0.0566
Difference	-	0.0042	0.0038	0.0054
	-	[1.41]	[1.36]	[1.01]
Share (ϕ)	-	0.1194	0.1080	0.1551
Avg. # pairs	-	5	25	9
Unique pairs	-	13	44	9
Fraction ITM	-	0.0654	0.0617	0.0741
N	162	162	162	162

	Panel B: Dollar-neutral (EQL-$N)			
	Unhedged	CN(10δ)	CN(10δ)	CN(10δ)
Hedging scheme	None	Hierarchical	Combinatorial	Combinatorial
Option set	-	I/J	I/J	I/USD
Mean	0.0282	0.0238	0.0227	0.0206
	[1.63]	[1.39]	[1.32]	[1.20]
Volatility	0.0635	0.0631	0.0632	0.0629
Skewness	-0.96	-0.54	-0.55	-0.46
Minimum	-0.0734	-0.0600	-0.0572	-0.0532
Difference	-	0.0044	0.0056	0.0076
	-	[1.60]	[2.10]	[1.34]
Share (ϕ)	-	0.1567	0.1966	0.2700
Avg. # pairs	-	8	20	9
Unique pairs	-	22	35	9
Fraction ITM	-	0.0664	0.0599	0.0741
N	162	162	162	162

Table A.VI
Returns to Crash-Neutral Currency Carry Trade Portfolios in G10 Currencies: Quarterly hedging

This table reports summary statistics for returns to spread-weighted portfolios of G10 currency carry trades, which have been crash-hedged using 10δ (out-of-the-money) FX options. The portfolio composition is rebalanced quarterly, and is determined by sorting currencies on the basis of their prevailing 3-month LIBOR rate, and going long (short) currencies with high (low) interest rates. Portfolio returns are computed over the period from January 1999 to June 2012 ($N = 54$ quarters), and are reported separately for non-dollar-neutral portfolios and dollar-neutral portfolios. The portfolios are hedged using the *hierarchical* hedging scheme, which uses the smallest possible number of unique currency options by matching the long and short exposures into pairings on the basis of their allocations in the unhedged carry portfolio. The hedging scheme uses the full set of 45 G10 cross-rate options (I/J). Means, volatilties and Sharpe ratios (SR) are annualized; t-statistics reported in square brackets. *Minimum* is the smallest observed monthly return. *Difference* reports the difference in the mean return of the unhedged and hedged portfolios (t-statistics in square brackets). *Share* (ϕ) captures the share of the jump risk premium in the total currency excess return, and is computed as the ratio of the difference between the unhedged and hedged portfolio returns, and the unhedged portfolio return. Finally, the table reports the average number of FX options in the portfolio at each point in time. *Unique pairs* reports the total number of unique currency pairs considered over the full span of the sample. *Fraction ITM* reports the fraction of FX options which expired in-the-money.

	Non-dollar-neutral (SPR)		**Dollar-neutral (SPR-$N)**	
	Unhedged	CN(10δ)	Unhedged	CN(10δ)
Hedging scheme	None	Hierarchical	None	Hierarchical
Option set	-	I/J	-	I/J
Mean	0.0566	0.0530	0.0505	0.0449
	[2.10]	[2.00]	[1.81]	[1.62]
Volatility	0.0989	0.0972	0.1023	0.1015
Skewness	-1.50	-1.14	-1.48	-1.08
Minimum	-0.1835	-0.1614	-0.0236	-0.1971
Difference	-	0.0036	-	0.0051
	-	[0.70]	-	[1.12]
Share	-	0.0633	-	0.1022
N (quarters)	54	54	54	54

Table A.VII
FX Variance and Skewness Risk Premia

This table examines the dynamics of realized ($\mathbb{P}$) and option-implied ($\mathbb{Q}$) moments of currency returns, as well as, their associated risk premia, using panel regressions. Realized moments (variance and skewness) are computed using daily intra-month currency excess returns. The notation, $M^{\mathbb{P}}_{t:t+1}$, indicates the moment was computed using the realized intra-month returns starting at the end of month t, through the end of month $t+1$. Option-implied moments are computed using the method of Bakshi, et al. (2003), and are based on implied volatility functions, which have been interpolated using the vanna-volga method, and extrapolated by appending flat tails for strikes below (above) the 10δ put (call). Option-implied moments, $M^{\mathbb{Q}}_t$, are computed as of the last day of month t. $xs^{ji}_{t-1:t}$ is the (lagged) log currency excess return for currency pair J/I computed from the end of month $t-1$, through the end of month t. $y^j_t - y^i_t$ is the one-month LIBOR differential between countries J and I, computed as of the end of month t. The unit of observation is a currency pair/month ($N = 45 \cdot 160 = 7200$), and the panel regression are carried out with currency pair fixed effects (coefficients not reported). The table reports coefficient estimates and the associated t-statistics (reported in square brackets) based on robust standard errors, which have been adjusted for within time-period cross-sectional correlation, as well as, time-series autocorrelation and cross-correlations applying the methodology of Thompson (2006) with three monthly lags. $Adj.\,R^2$ is the regression adjusted R^2; $Adj.\,R^2\,[NFE]$ is the regression adjusted R^2 reported net of the explanatory power of the fixed effects.

	$\mathrm{Var}^{\mathbb{P}}_{t:t+1}$	$\mathrm{Var}^{\mathbb{Q}}_t$	$\mathrm{Var}^{\mathbb{Q}}_t - \mathrm{Var}^{\mathbb{P}}_{t:t+1}$	$\mathrm{Skew}^{\mathbb{P}}_{t:t+1}$	$\mathrm{Skew}^{\mathbb{Q}}_t$	$\mathrm{Skew}^{\mathbb{Q}}_t - \mathrm{Skew}^{\mathbb{P}}_{t:t+1}$
$xs^{ji}_{t-1:t}$	-0.07	-0.08	-0.01	-1.77	2.16	3.93
	[-2.32]	[-1.58]	[-0.20]	[-8.30]	[11.66]	[6.70]
$y^j_t - y^i_t$	0.06	0.03	-0.02	-3.90	-1.15	2.74
	[1.46]	[1.03]	[-0.65]	[-4.31]	[-3.01]	[2.72]
FX pair FE	Y	Y	Y	Y	Y	Y
R^2	0.07	0.13	0.00	0.05	0.53	0.08
$R^2[NFE]$	0.01	0.02	0.00	0.02	0.10	0.04
N	7200	7200	7200	7200	7200	7200