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DYNAMIC INTERACTIONS BETWEEN GOVERNMENT BONDS AND EXCHANGE RATE EXPECTATIONS IN CURRENCY OPTIONS

Key points:

- *Option markets have the desirable property of being forward-looking in nature and thus are a useful source of information for gauging market sentiment about future values of financial assets. Currency options, whose payoff depends on a limited range of the expected exchange rate, offer information about market expectations on both future exchange rate level and volatility.*

- *This paper examines the dynamic interactions between government bonds of Germany, Japan and the US and their exchange rate expectations anticipated in the currency options, i.e., risk reversals (put premia) of the US dollar versus the yen and euro.*

- *We find evidence of one-way information flow from the government bond market to the currency option market. The flow was relatively short term before the global financial crisis and was substantial during the post-crisis period when the US Fed started quantitative easing (QE). However, it diminished after the 2013 taper tantrum. This demonstrates that the US's QE which compressed its long-term bond yields could substantially affect the dollar exchange rate expectations reflected in the currency option prices.*

- *The long-term bond yields of the US (UST), Japan (JGB) and Germany (Bund) are important and separable determinants of the risk reversals in the US-QE period for the dollar-yen exchange rate and the pre-crisis period for the euro-dollar exchange rate. The negative relationship between the spreads of the UST yield over the JGB/Bund yields and the risk reversals indicates that a lower US dollar interest rate can coincide with a dollar depreciation expectation embedded in the currency option prices. The result implies that a fall in US dollar interest rates leads to a depreciation of the US dollar, not appreciation as predicted by uncovered interest rate parity.*

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I. INTRODUCTION

Option markets have the desirable property of being forward-looking in nature and thus are a useful source of information for gauging market sentiment about future values of financial assets. Currency options, whose payoff depends on a limited range of the expected exchange rate, offer information about market expectations on both future exchange rate level and volatility. Currency option prices with different strike prices are quoted in the market using the Black-Scholes implied volatilities, which assume that interest rate parity holds in the pricing framework developed by Garman and Kohlhagen (1983). This parity condition states that the domestic interest rate should equal the foreign interest rate plus the expected change of the exchange rate. Therefore, the Black-Scholes/Garman-Kohlhagen pricing model assumes that, in a risk-neutral market, future exchange rates perfectly adjust given the present interest-rate differentials.

However, as option dealers only use the Black-Scholes model to convert quoted volatilities to option prices, or vice versa, the assumptions of constant parameters in the model are consistent with the existence of a "non-flat" implied volatility structure since, the options can also price in expectations on future exchange rate levels. In particular, a risk reversal is an option strategy that speculates on the future skewness of the exchange rate distribution by simultaneously buying (selling) an out-of-the-money call and selling (buying) an out-of-the-money put. It is quoted as the difference between option-implied volatility of the put and call with the same (absolute) delta.[1] A positive risk

[1] The Black-Scholes deltas of call and put options are given by

$$\Delta_{call} = e^{-q\tau}N(d_1), \quad \Delta_{put} = -e^{-q\tau}N(-d_1), \quad d_1 = \frac{\ln\left(\frac{Se^{(r-q)\tau}}{K}\right) + \frac{1}{2}\sigma_{imp}^2\tau}{\sigma_{imp}\sqrt{\tau}}$$

where S is the dollar-yen (euro) exchange rate, K is the strike price, σ_{imp} is the implied volatility, q and r are the US dollar and yen (euro) interest rates, τ is the time-to-maturity and $N(.)$ is the cumulative normal distribution. Mathematically, the 10-delta risk reversal is given by reversal (put premium) position suggests that the traders expect the currency to depreciate. Campa et al. (1998) and Carr and Wu (2007) provide evidence that, when out-of-the-money put prices increase relative to out-of-the-money call prices, the corresponding currency depreciates. Farhi et al. (2015) confirm this result on a larger sample of currencies.

The link between currency option prices and interest rates has been studied in the context of currency carry trades, which consist of selling low interest-rate currencies (funding currencies) and investing in high interest-rate currencies (investment currencies). Brunnermeier et al. (2009) document that carry traders are subject to crash risk. Therefore, exchange rate movements between high-interest-rate and low-interest-rate currencies are negatively skewed. The price of currency crash risk is reflected by the price of the risk reversal. Jurek (2014) derives a measure of crash risk from currency options and finds that exposure to a currency crash can be used to explain a significant portion of carry trade returns. Farhi and Gabaix (2016) propose a model of exchange rates, based on the hypothesis that the possibility of rare but extreme disasters is an important determinant of risk premia in asset markets. They show that the model is empirically consistent with the link between exchange rates of currencies with high interest rates and disaster risk reflected from risk reversals.

Different from previous studies that focus on carry trades on emerging markets and commodity currencies, this paper examines the dynamic relationship between government bond yields in the advanced economies, of Germany, Japan and the US, and their exchange rate expectations embedded in the prices of currency options, measured by risk reversals (put premia) of the US dollar versus the yen and euro, covering the periods before and after the global financial crisis. First, we study the information transmission between the government bond

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$$rr10 = IV(\Delta_{put} = 10) - IV(\Delta_{call} = 10),$$

where $IV(\Delta_{put} = x)$ and $IV(\Delta_{call} = x)$ denote the implied volatilities of the put and call with x-delta. The Black-Scholes delta provides a normalised measure of option moneyness, where the delta of a European option increases monotonically from 0 to 100, with the moneyness moving from out-of-the-money to in-the-money.

and currency option markets to examine whether currency option prices anticipate information from bond yields. Secondly, we investigate whether government bond yields is an important and separable determinant of the risk reversals, after controlling for global risk appetite, funding liquidity constraint and macro-financial condition.

This paper is also related to recent literature on interconnectivity and the information transmission between markets. Acharya and Johnson (2007) find there is incremental information flow from the corporate credit default swap (CDS) market to the stock market. They show that the corporate CDS market leads the stock market to anticipate adverse credit information of the reference firm and this finding is linked to informed-trading in credit derivatives. Cremers et al. (2008) indicate that implied volatilities of individual stock options contain important information for credit spreads of the underlying stocks. Cao et al. (2010) show that options market information is highly relevant when explaining the pricing of corporate CDS. They identify a robust predictability of future corporate CDS spread changes from current implied volatility innovations of equity options, i.e., information flow from option prices to CDS spreads. Hui and Chung (2011) find evidence of information flow from the sovereign CDS market to the euro-dollar currency option market during the European sovereign debt crisis. Similarly, the finding in this paper demonstrates that currency option prices contain information transmitted from government bond yields.

We have the following findings: (i) there was one-way information flow from the government bond market to the currency option market, which diminished after the 2013 taper tantrum.; (ii) the long-term bond yields are important and separable determinants of the risk reversals after controlling for other factors; and (iii) the negative relationship between the spreads of the US bond yield over the other two countries' bond yields and risk reversals indicating a fall in US dollar interest rate implies dollar depreciation expectations embedded in the currency option prices. These findings provide new empirical understanding about interactions between the government bond and currency markets in the developed economies.

II. Information flow between the government bond market and currency option market

In this section, we adopt a systematic approach suggested by Acharya and Johnson (2007) to investigate the information transmission between the government bond market of Germany, Japan, and the US and their currency option market. In particular, we examine whether currency option prices contain information on the corresponding differences between the bond yields, indicating that the two markets possessing two different but inter-dependent information sets.[2] The price innovations in the two markets are the market-specific information arrivals in addition to the market-wide information set.[3] If the government bond market contains forward-looking information and affects expectations of exchange rates, then the innovation of the bond yield differential between the economies can predict future changes in risk reversals and expectations of future exchange rate movements.

We collect daily data of the 3-month and 10-year government bond yields of the US (UST) at 17:20 EST for both 10-year and 3-month maturities; Japan (JGB) at 05:00 EST for 10-year maturity and 20:30 EST for 3-month maturity; and Germany (Bund) at 12:00 EST for 10-year maturity and 20:30 EST for 3-month maturity from January 2, 2001 to July 29, 2016.[4] The 3-month and 10-year tenors represent the short- and long-term interest rates, respectively. We then obtain at 11:00 EST daily over-the-counter, European-style 3-month 10-delta risk reversals of dollar-yen and euro-dollar option quotes for the same period.[5]

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[2] Acharya and Johnson (2007) empirically investigate whether the CDS market acquires information prior to the stock market. By controlling the contemporaneous interaction between the two markets, they extract the market-specific innovations and study the structure of information flow between the two markets. These innovations can then be interpreted as the market-specific information arrival to the particular markets.

[3] Formally, we consider a probability space $(\Omega, \mathfrak{I}, \mathbb{Q})$, where $\mathbb{Q}$ is the risk-neutral measure in an arbitrage-free economy, $\mathfrak{I}_t$ is the filtration generated by the underlying state variables (the overall financial market) in such a way that $\mathfrak{I}_t = G_t \vee H_t$, where G_t and H_t are the information sets of the government bond market and currency option market respectively.

[4] We collect the government bond data from Bloomberg. The yields are generic yield quotes except for 3-month JGB and 3-month Bund of which the historical data of the generic quotes are not long enough to cover the full sample period. We use the zero-coupon quotes for these two yields instead.

[5] The data are from JPMorgan.

A risk reversal quote is the implied volatilities of a 10-delta put minus a 10-delta call on the US dollar. We choose the 3-month maturity as the benchmark because it conveys both short-term and long-term views of market participants. Table 1 presents the descriptive statistics for the bond yields and 3-month risk reversals.

We obtain the market-specific price innovations in the government bond market by the regression:

$$\Delta GB_t = a + b\Delta RR_t + \sum_{k=1}^{n} c_k \Delta GB_{t-k} + \varepsilon_{GB,t} \qquad (1)$$

where $\Delta \mathrm{GB}_t$ is the change in the spread of the UST yield over the JGB or Bund yield (or their individual bond yields), $\Delta \mathrm{RR}_t$ is the change in the 3-month 10-delta risk reversal. The lagged information transmission in the government bond market is captured by the lagged changes in the bond spread (or yield), and the market-specific innovation $\varepsilon_{\mathrm{GB},t}$ can be identified as an independent information arrival that is unanticipated by the currency option market at time t. We then model the information flow from the government bond market to the currency option market by the following regression:

$$\Delta RR_t = \alpha + \sum_{k=1}^{n} \beta_k \varepsilon_{GB,t-k} + \sum_{k=1}^{n} \gamma_k \Delta RR_{t-k} + \varepsilon_{RR,t} \qquad (2)$$

where lagged market-specific innovations $\varepsilon_{GB,t}$ are used to explain the changes in the risk reversal. The lagged influences of the innovations are reflected by the loading coefficients β_k, k = 1, 2, …, n.[6] The intensity of the information flow can be accessed by the statistical significance of the point estimate $I = \sum_{k=1}^{n} \beta_k$, as suggested by Acharya and Johnson (2007).

Similarly, the reverse information flow from the currency option market to the government bond market is analysed by the regressions:

$$\Delta RR_t = \tilde{a} + \tilde{b}\Delta GB_t + \sum_{k=1}^{n} \tilde{c}_k \Delta RR_{t-k} + \tilde{\varepsilon}_{RR,t} \qquad (3)$$

[6] We employ the Wald test for coefficient restriction with the null hypothesis $\sum_{k=1}^{n} \beta_k = 0$. Since information is usually reflected in prices within a week, we only present the estimation results from n = 2 to n = 5.

$$\Delta GB_t = \tilde{\alpha} + \sum_{k=1}^{n} \tilde{\beta}_k \tilde{\varepsilon}_{RR,t-k} + \sum_{k=1}^{n} \tilde{\gamma}_k \Delta GB_{t-k} + \tilde{\varepsilon}_{GB,t} \tag{4}$$

where the intensity of the reverse information flow is measured by $\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$. If the information flow is one-way and permanent from the government bond market to the currency option market, I should be statistically significant and $\tilde{I}$ should be insignificant.

We study information flow between the government bond and currency option markets in the following three periods: (A) the pre-global financial crisis period until the US federal funds rate reached the zero lower bound (from January 2, 2001 to December 16, 2008); (B) the post-crisis period when the US Fed embarked on a quantitative easing (QE) program (from December 17, 2009 to May 21, 2013); and (C) the period since the anticipation of QE tapering (from May 22, 2013 to July 29, 2016).

Table 2 shows the estimation results for the dollar-yen risk reversal. There was substantial information flow from the 10-year and 3-month UST-JGB yield spreads to the risk reversal with significant negative I in the US-QE period (period B). In the pre-crisis period (period A), short-term, one-way information flow is observed from the 10-year UST-JGB yield spread to the risk reversal, while two-way information flow between the two markets is found for the 3-month yield spread. During the tapering period (period C), there was very short-term information flow from the 10-year yield spread to the risk reversal and opposite information flow for the 3-month yield spread. The results, in general, indicate that the information flow, though transient in nature, was primarily from the UST and JGB markets to the dollar-yen option market.

To further examine the contributions of the bond yields, the estimations using individual bond yields show that robust one-way information flow was from the 10-year UST yield to the risk reversal in the US-QE period, probably indicating the effects of the US's QE, which compressed the long-term interest rates on the dollar exchange rate expectation. Both the 3-month UST and

JGB yields also provided one-way information flow to the risk reversal in this period. This demonstrates that the currency option market contained the information in both the US and Japanese short-term bond markets. In the pre-crisis period, while there was one-way information flow from the 10-year UST yield to the risk reversal, both the 3-month UST and JGB yields had two-way information flow to the risk reversal. Regarding the tapering period, scattered two-way information flow is found from the bond yields to the risk reversal.

The negative information flow intensity I for the UST-JGB yield spreads and UST yields shows that the risk reversal is negatively related to the US interest rates. Conversely, the positive information flow intensity I for the JGB yields suggests that the risk reversal is positively related to the Japanese interest rates. The signs indicate that a rise in the US interest rates (or a decline in the Japanese interest rates) leads to an appreciation expectation of the US dollar in the currency option market, i.e., a lower risk reversal (dollar put premium). Given that uncovered interest parity (UIP) predicts a high interest rate currency will depreciate relative to a low interest rate currency, the result shows participants in the currency option market expect UIP to fail. Such expectation in the currency option market is consistent with the finding by Bruno and Shin (2015) that UIP fails for the emerging market currencies with high interest rates versus low interest rates in advanced economies. As there were significant carry trades of investing the US dollar funded by the yen in the currency market, the information flows indicated that carry traders would hedge their positions by buying US dollar puts (yen calls) that increased the risk reversal (dollar put premia) when the UST-JGB yield spreads narrowed.[7] This suggests that, while crash risk is hedged in advance in some carry-trade positions by buying US dollar puts, substantial carry-trade positions are hedged when the yield spreads narrow.

The estimation results for the UST and Bund yields, and euro-dollar risk reversals, are presented in Table 3. In the pre-crisis period, scattered one-way

[7] Using the BIS international banking statistics data, Galati, Health and McGuire (2007) find evidence of the increase in carry trade activities funded by Japanese yen and Swiss franc in the period from 2002Q2 to 2007Q1.

information flow with negative I is found from the 10-year UST-Bund yield spread and 3-month UST yield to the risk reversal. During the US-QE period, there was substantial one-way information flow from the 10-year UST and Bund yields to the dollar-euro risk reversal with positive I. However, short-term reverse information flow is found for the 3-month UST-Bund yield spread and Bund yield. In the tapering period, almost no information flow is observed between the two markets. Similar to the results for Japan and the US, the information transmission was dominantly from the US and German government bond markets to the currency option market and was transient in nature.

III. CONTEMPORANEOUS INTERACTIONS BETWEEN GOVERNMENT BOND YIELDS AND CURRENCY OPTION PRICES

The previous section shows the interconnectivity and lead-lag relationship between the government bond market and option currency market. To better understand the economic sources of such linkages, we use regression analysis to study how expectations of exchange rate movements anticipated in the currency option market is attributed to bond yields of the US, Japan and Germany. Based on the one-way information flow from the bond market to the currency option market identified in the previous section, we test the following three hypotheses:

(i) Government bond yields are an important and separable factor to explain risk reversals;

(ii) An increase in the UST yield relative to the JGB or Bund yield reduces the risk reversals of the US dollar; and

(iii) Only the long-term yields or yield spreads have effects on the risk reversals.

We first study the contemporaneous interactions between the government bond yields (spreads) and the 3-month risk reversals by the regression:

$$\Delta RR_t = \sum_{k=1}^{2} \gamma_k \Delta RR_{t-k} + \alpha + \beta \Delta GB_t + \varepsilon_t, \tag{5}$$

where ΔRR_t is the change in the 3-month 10-delta risk reversal and ΔGB_t is the change in the government bond yield (spread). We use the weekly data (last day of each week) to avoid the influence from the short-term lead-lag relationship. The lagged terms $\sum_{k=1}^{2} \gamma_k \Delta RR_{t-k}$ are added to correct the serial correlations in the residuals.

To examine if the government bond yields are a separate factor to explain the risk reversals, a set of macro-financial variables as control variables are added to Eq.(5), including the following factors:

(i) *US dollar volatility*. The option-implied volatility of an exchange rate may anticipate uncertainty on the exchange rate based on the realised actual volatility. Therefore, we use the US dollar index (DXY), a weighted average of the dollar's value relative to a basket of foreign currencies, to capture the actual volatility attributable to the dollar factor. We proxy the volatility of the US dollar ($\Delta \boldsymbol{r}_{\boldsymbol{USD}}^{\boldsymbol{2}}$) as the ex-post squared return of the index.

(ii) *Global risk appetite*. We use the CBOE VIX volatility index (*VIX*), the option-implied volatility of the US S&P 500 index, to gauge the global risk appetite in the financial market. Currency option-implied volatility shares commonality with the VIX index as a measure of investors' aversion to risky exposure. Given that the yen is the strongest safe-haven currency, followed by the US dollar, according to some studies, we expect the VIX index to have a positive relationship with the dollar-yen risk reversal and a negative relationship with the euro-dollar risk reversal.[8]

(iii) *Funding liquidity constraint*. When funding liquidity is tight, traders are forced to unwind their carry-trade positions and repatriate funds to funding currencies. We follow Brunnermeier et al. (2009) and use the US-dollar TED spread (*TED*), the difference between the 3-month interbank rate and the 3-month Treasury bill yield, to capture traders' funding liquidity constraint. A positive

[8] See Ranaldo and Söderlind (2010) and Habib and Stracca (2012) about the studies of safe-haven currencies.

relationship is expected between the TED spread and the dollar-yen and euro-dollar risk reversals when the yen or euro are the funding currencies.

(iv) *Macro-financial condition*. To capture the broad changes in the macro-financial condition, we include a measure from the stock markets that has been used by Collin-Dufresne et al. (2001), Cremers et al. (2008), and Cao et al. (2010). We use the weekly returns of the S&P 500 index (*SPX*), Nikkei 225 index (*NKY*) and Dow Jones EURO STOXX 600 index (*STOXX*) for the US, Japanese and euro-area markets respectively. As an appreciated currency is usually associated with weakening exports and underperformance of its stock market, we expect the Nikkei 225 index and Dow Jones EURO STOXX 600 index to be negatively related to the risk reversals of the dollar (expectations on a weakened dollar). Given that the US macro-financial condition will have a reverse effect on the exchange rate, the S&P 500 is positively related to the risk reversals.

After incorporating all these control variables in Eq.(5), the regression becomes:

$$\Delta RR_t = \sum_{k=1}^{2} \gamma_k \Delta RR_{t-k} + \alpha + \beta_1 \Delta GB_t + \beta_2 \Delta r_{USD,t}^2 + \beta_3 \Delta VIX_t + \beta_4 \Delta TED_t + \beta_5 \Delta SPX_t + \beta_6 \Delta NKY_t + \varepsilon_t \quad (6a)$$

for the dollar-yen risk reversal; and

$$\Delta RR_t = \sum_{k=1}^{2} \gamma_k \Delta RR_{t-k} + \alpha + \beta_1 \Delta GB_t + \beta_2 \Delta r_{USD,t}^2 + \beta_3 \Delta VIX_t + \beta_4 \Delta TED_t + \beta_5 \Delta SPX_t + \beta_6 \Delta STOXX_t + \varepsilon_t \quad (6b)$$

for the euro-dollar risk reversal. If the government bond yields (spreads) are a separable explanatory factor, the coefficient β_1 should be significant in both Eqs.(5) and (6).

Tables 4-6 show regression results during the pre-crisis, US-QE and tapering periods respectively. When the control macro-financial variables are significant, they show the expected signs of estimations. Table 4 shows that the 10-year UST-Bund yield spread is significant without and with the control variables under Eqs.(5) and (6) respectively. This demonstrates that the yield spread between the 10-year UST and Bund is an important and separable factor to explain the euro-dollar risk reversal during the pre-crisis period. The corresponding negative coefficient reflects that an increase in the UST yield relative to the Bund yield reduces the risk reversal, consistent with the signs of the information flow estimations. Both the 10-year UST-JGB yield spread and UST yield for the dollar-yen risk reversal and the 3-month UST yield for the euro-dollar risk reversal are significant without the control variables, but they become insignificant with the control variables included.

Table 5 shows that the 10-year UST-JGB yield spread and 10-year UST yield are both significant with and without the control variables for the dollar-yen risk reversal during the US-QE period. The corresponding coefficients are negative. Meanwhile, the 3-month UST-JGB yield spread and their respective yields are insignificant with and without the control variables. The 10-year UST and Bund yields are significant for the euro-dollar risk reversal without the control variables, but they become insignificant with the control variables. The results in the US-QE period indicate that the 10-year UST yield and its spread over the JGB yield are important and separable factors to explain the dollar-yen risk reversal, and an increase in the UST yield relative to the JGB yield reduces the risk reversal.

Table 6 shows the 10-year UST-JGB yield spread is significant without the control variables for the dollar-yen risk reversal during the tapering period, but becomes insignificant with the control variables incorporated. The corresponding coefficients are negative.

In summary, the regression results support the three hypotheses regarding the dynamic interactions between the UST and JGB yields and the dollar-yen risk reversal during the US-QE period. For the euro-dollar risk reversal, the three hypotheses are shown to be valid only in the pre-crisis period.

IV. CONCLUSION

This paper examines the dynamic interactions between government bonds of Germany Japan and the US and their exchange rate expectations anticipated in the currency options, i.e., risk reversals (put premia) of the US dollar versus the yen and euro. We find evidence of one-way information flow from the government bond market to the currency option market. The flow was substantial during the post-global financial crisis period when the US Fed started QE, while it was relatively short term before the global financial crisis and diminished after the 2013 taper tantrum. This demonstrates that the US's QE, which compressed its long-term bond yields, could substantially affect the dollar exchange rate expectations reflected in the currency option prices.

Further econometric analysis indicates that the long-term bond yields of the UST, JGB and Bund are important and separable determinants of the risk reversals in the US-QE period for the dollar-yen exchange rate and the pre-crisis period for the euro-dollar exchange rate. The negative relationship between the spreads of the UST yield over the JGB/Bund yields and the risk reversals indicates that a lower US dollar interest rate can coincide with a dollar depreciation expectation embedded in the currency option prices after controlling for global risk appetite, funding liquidity constraint and macro-financial condition. The result is consistent with the finding by Bruno and Shin (2015) that a fall in US dollar interest rates leads to a depreciation of the US dollar versus emerging economies' currencies, not an appreciation, as predicted by UIP.

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Table 1

Descriptive statistics for the US Treasury (UST) yields, the Japanese government bond (JGB) yields, the German government bond (Bund) yields, and the risk reversals.

	UST (%)		JGB (%)		Bund (%)		Risk reversal (%)	
	10-year	3-month	10-year	3-month	10-year	3-month	Dollar-yen	Dollar-euro
Full sample: From January 2, 2001 to July 29, 2016								
Mean	3.49	1.42	1.13	0.11	3.01	1.64	2.24	-0.99
Median	3.69	0.61	1.28	0.06	3.34	1.99	1.56	-0.54
Maximum	5.54	5.87	2.01	0.67	5.28	4.90	19.14	2.57
Minimum	1.37	0.00	-0.29	-0.34	-0.19	-0.73	-3.35	-8.05
Std. dev.	1.11	1.70	0.47	0.16	1.42	1.62	2.93	1.94
Skewness	-0.16	1.03	-0.66	1.04	-0.52	0.30	2.17	-0.94
Kurtosis	1.74	2.65	2.84	3.91	2.08	1.68	10.60	3.67
No. of observations	3894	3894	3883	3898	3898	3898	3897	3897
(A) From January 2, 2001 to December 16, 2008								
Mean	4.42	2.70	1.43	0.15	4.15	3.07	2.56	0.34
Median	4.41	2.21	1.44	0.02	4.13	3.15	1.66	0.37
Maximum	5.54	5.87	2.01	0.67	5.28	4.90	19.14	2.57
Minimum	2.37	0.00	0.45	0.00	3.02	1.52	-3.35	-4.68
Std. dev.	0.51	1.53	0.28	0.20	0.51	0.87	3.12	0.84
Skewness	-0.24	0.32	-0.84	0.81	0.08	0.26	2.41	-0.68
Kurtosis	2.93	1.65	4.25	1.88	2.49	1.79	11.28	5.03
No. of observations	1989	1989	1979	1992	1992	1992	1992	1992
(B) From December 17, 2008 to May 21, 2013								
Mean	2.68	0.10	1.09	0.12	2.47	0.39	2.44	-2.69
Median	2.77	0.10	1.12	0.10	2.65	0.31	2.07	-2.71
Maximum	4.01	0.32	1.56	0.43	3.72	1.58	16.71	1.73
Minimum	1.43	0.00	0.45	0.03	1.17	0.00	-2.81	-8.05
Std. dev.	0.75	0.06	0.24	0.05	0.76	0.33	3.17	2.13
Skewness	-0.01	0.55	-0.31	2.27	-0.26	0.93	1.28	-0.21
Kurtosis	1.51	3.54	2.09	8.91	1.52	3.31	5.69	2.64
No. of observations	1106	1106	1105	1106	1106	1106	1106	1106
(C) From May 22, 2013 to July 29, 2016								
Mean	2.30	0.09	0.42	-0.01	0.92	-0.19	1.14	-1.98
Median	2.28	0.04	0.46	0.00	0.80	-0.13	0.96	-1.73
Maximum	3.04	0.36	0.93	0.10	2.05	0.15	5.20	0.20
Minimum	1.37	0.00	-0.29	-0.34	-0.19	-0.73	-1.71	-4.72
Std. dev.	0.37	0.10	0.28	0.10	0.61	0.23	1.43	0.89
Skewness	-0.20	1.41	-0.73	-1.75	0.18	-0.54	0.74	-0.70
Kurtosis	2.24	3.39	2.94	5.54	1.71	2.12	3.20	2.79
No. of observations	799	799	799	800	800	800	799	799

Note: We report the full sample and the sub-samples summary statistics on (1) the UST, JGB and Bund yields at the maturities of 10 years and 3 months; and (2) the dollar-yen and dollar-euro risk reversals at maturity of 3 months with 10-delta strike. The statistics are based on daily sampled data. The government bond yields and the risk reversals are all in percentage points.

Table 2

Information flow between dollar-yen option market (risk reversal) and UST-JGB market.

Number of lags included, *n*		UST-JGB yield spread 10-year	UST-JGB yield spread 3-month	UST yield 10-year	UST yield 3-month	JGB yield 10-year	JGB yield 3-month
(A) Sample period: from January 2, 2001 to December 16, 2008							
$I=\sum_{k=1}^{n}\beta_k$	2	-0.5254 **	-0.6007 **	-0.5184 **	-0.5448 **	0.3688	4.0556 **
	3	-0.6301 **	-0.2609	-0.6271 *	-0.2038	0.1543	3.6254 *
	4	-0.4557	-0.7182 **	-0.4654	-0.6420 *	-0.0263	3.3926
	5	-0.5425	-0.6238	-0.7456 *	-0.5464	-0.5525	4.2525
$\tilde{I}=\sum_{k=1}^{n}\tilde{\beta}_k$	2	0.0097	-0.0590 **	0.0060	-0.0543 **	-0.0023	0.0039 **
	3	0.0185	-0.0715 **	0.0154	-0.0641 **	0.0012	0.0042 **
	4	0.0206	-0.0991 **	0.0104	-0.0892 **	-0.0038	0.0056 **
	5	0.0262	-0.0974 **	0.0134	-0.0927 **	-0.0092	0.0001
(B) Sample period: from December 17, 2008 to May 21, 2013							
$I=\sum_{k=1}^{n}\beta_k$	2	-1.0593 **	-2.3653 *	-1.1755 **	-0.6597	-0.0231	4.0052 *
	3	-1.1079 **	-3.5358 **	-1.3195 **	-1.2633	-0.6537	5.6604 **
	4	-0.9551 *	-5.9525 **	-1.1046 **	-2.6421 *	-0.8078	7.2971 *
	5	-1.3836 **	-8.8781 **	-1.5363 **	-4.5988 **	-0.3069	9.0484 *
$\tilde{I}=\sum_{k=1}^{n}\tilde{\beta}_k$	2	0.0080	0.0016	0.0085	0.0030	-0.0040	-0.0009
	3	0.0089	-0.0010	0.0120	0.0018	-0.0036	0.0014
	4	0.0198	-0.0004	0.0217	0.0039	-0.0042	0.0022
	5	0.0056	-0.0019	0.0048	0.0035	-0.0050	0.0025
(C) Sample period: from May 22, 2013 to July 29, 2016							
$I=\sum_{k=1}^{n}\beta_k$	2	-0.6209 *	-0.2750	-0.3675	-0.7763	1.6501 *	-0.6880
	3	-0.3282	-2.1128	-0.2682	-3.4811 *	1.7081	-0.5310
	4	-0.1138	-0.9203	0.0547	-2.2557	2.4351 *	-1.2954
	5	-0.0189	-1.2230	0.1319	-3.5318	2.5977	-3.1484
$\tilde{I}=\sum_{k=1}^{n}\tilde{\beta}_k$	2	-0.0078	-0.0050	-0.0097	-0.0023	-0.0105 *	0.0027
	3	-0.0223	-0.0082	-0.0204	-0.0049	-0.0119 *	0.0035
	4	-0.0181	-0.0135 *	-0.0157	-0.0090 *	-0.0126	0.0050
	5	-0.0131	-0.0074	-0.0111	-0.0042	-0.0131	0.0041

Note: This table summarises the estimation results of Eqs.(1)-(4) for analysing the information flow between the dollar-yen option risk reversal and the UST-JGB yield spreads, UST yields and JGB yields.

* Significance at 5% level respectively.

** Significance at 1% level respectively.

Table 3

Information flow between euro-dollar option market (risk reversal) and UST-Bund market.

Number of lags included, n		UST-Bund yield spread 10-year	UST-Bund yield spread 3-month	UST yield 10-year	UST yield 3-month	Bund yield 10-year	Bund yield 3-month
(A) Sample period: from January 2, 2001 to December 16, 2008							
$I = \sum_{k=1}^{n} \beta_k$	2	-0.1375	-0.0808	-0.0742	-0.0404	-0.0822	0.2389
	3	-0.2677	-0.2250 *	-0.0727	-0.2255 *	0.0579	0.2049
	4	-0.4164 *	-0.2244 *	-0.0809	-0.1264	0.1465	0.5706 *
	5	-0.3849	-0.6047 **	0.0427	-0.4831 **	0.3634	0.6359 *
$\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$	2	-0.0045	0.0241	-0.0030	0.0132	0.0005	-0.0103
	3	-0.0178	0.0533 *	-0.0165	0.0318	-0.0051	-0.0269 **
	4	-0.0223	0.0660 *	-0.0146	0.0465	-0.0049	-0.0267 *
	5	-0.0187	0.0984 **	-0.0493	0.0299	-0.0444 *	-0.0765 **
(B) Sample period: from December 17, 2008 to May 21, 2013							
$I = \sum_{k=1}^{n} \beta_k$	2	-0.2544	0.2016	0.6614 **	-0.2721	1.1554 **	-0.2193
	3	-0.1505	0.0718	0.7086 **	0.9037	1.2159 **	-0.0165
	4	-0.1201	-0.1987	0.9568 **	1.0288	1.5003 **	0.2958
	5	-0.4414	-0.0978	0.9000 **	2.4311	1.7738 **	0.2431
$\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$	2	0.0143	0.0289 *	-0.0036	0.0047	-0.0151	-0.0233 *
	3	0.0081	0.0562 **	-0.0048	0.0031	-0.0063	-0.0524 **
	4	0.0022	0.0361	-0.0217	0.0003	-0.0168	-0.0372
	5	0.0079	0.0106	-0.0128	0.0021	-0.0145	-0.0133
(C) Sample period: from May 22, 2013 to July 29, 2016							
$I = \sum_{k=1}^{n} \beta_k$	2	-0.3465	-0.6615	-0.3648	-0.6787	-0.1018	0.6041
	3	-0.0866	-0.2896	-0.2775	0.8830	-0.1261	1.0511
	4	-0.0861	0.4139	-0.1354	2.9356	-0.0131	0.9407
	5	-0.9235	0.0233	-0.7312	2.0049	-0.1706	0.8371
$\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$	2	-0.0004	-0.0082	-0.0077	0.0006	-0.0066	0.0078
	3	0.0100	-0.0022	0.0081	0.0051	-0.0015	0.0068
	4	0.0089	0.0028	-0.0186	0.0055	-0.0233	-0.0003
	5	0.0078	0.0167	-0.0520	-0.0024	-0.0502 *	-0.0160

Note: This table summarises the estimation results of Eqs.(1)-(4) for analysing the information flow between the dollar-euro option risk reversal and the UST-Bund yield spreads, UST yields and Bund yields.

* Significance at 5% level respectively.

** Significance at 1% level respectively.

Table 4

Determinants of changes in 3-month 10-delta dollar-yen/euro risk reversal for the period from January 5, 2001 to December 12, 2008.

Dependent variable:	Dollar-yen risk reversal (%)				Dollar-euro risk reversal (%)			
	(A) 10-year UST-JGB yield spread		(B) 10-year UST yield		(C) 10-year UST-Bund yield spread		(D) 3-month UST yield	
	(II)	(I)	(II)	(I)	(II)	(I)	(II)	(I)
Dollar-yen/euro risk reversal at time *t*-1 (%)	-0.0312	-0.0822	-0.0325	-0.0841	-0.1134 *	-0.1257 **	-0.1105 *	-0.1250 *
Dollar-yen/euro risk reversal at time *t*-2 (%)	0.0736	0.1050 *	0.0736	0.0990 *	-0.1721 **	-0.2004 **	-0.1733 **	-0.2066 **
Constant	-0.0244	0.0342	-0.0241	0.0328	0.0418 *	-0.0076	0.0400 *	-0.0103
Government bond yield (spread) (%)	-0.4629	-0.8635 **	-0.3832	-1.0577 **	-0.6373 **	-0.6045 **	-0.1656	-0.2865 *
Dollar squared return ($\%^2$)	362.6300 *		363.9518 *		-390.0789 **		-381.9196 **	
VIX index (%)	0.0775 **		0.0780 **		-0.0323 **		-0.0328 **	
US TED spread (%)	0.6163 *		0.6169 *		0.2899 **		0.2076	
US stock market return (%)	2.3105		2.1819		1.3701		1.2208	
Japanese/European stock market return (%)	-5.2404 **		-4.9336 **		-3.7721 **		-3.7990 **	
R-squared	25.3%	4.0%	25.1%	5.1%	20.8%	7.0%	19.0%	6.3%
Adjusted R-squared	23.8%	3.3%	23.7%	4.4%	19.3%	6.3%	17.4%	5.6%
Log-likelihood	-437.1	-489.1	-437.5	-486.7	-99.8	-133.2	-104.6	-134.7
F-statistic	17.18	5.75	17.04	7.37	13.35	10.30	11.87	9.21
No of observations	415		415		415		415	

Note: This table summarises the estimation results of Eqs.(5)-(6) for the pre-crisis period (January 5, 2001 to December 12, 2008) using the weekly changes.
* Significance at 5% level respectively.
** Significance at 1% level respectively.

Table 5

Determinants of changes in 3-month 10-delta dollar-yen/euro risk reversal for the period from December 19, 2008 to May 17, 2013.

Dependent variable:	Dollar-yen risk reversal (%)							
	(A) 10-year UST-JGB yield spread		(B) 3-month UST-JGB yield spread		(C) 10-year UST yield		(D) 3-month UST yield	
	(II)	(I)	(II)	(I)	(II)	(I)	(II)	(I)
Dollar-yen/euro risk reversal at time *t*-1 (%)	-0.1340 *	-0.1285 *	-0.1393 *	-0.1603 *	-0.1377 *	-0.1256 *	-0.1388 *	-0.1596 *
Dollar-yen/euro risk reversal at time *t*-2 (%)	0.0517	0.0641	0.0751	0.0913	0.0430	0.0639	0.0757	0.0920
Constant	-0.0948	-0.0813	-0.0915	-0.0779	-0.1002	-0.0861	-0.0918	-0.0811
Government bond yield (spread) (%)	-1.2146 **	-1.7386 **	-0.3847	-1.8571	-1.4743 **	-1.8998 **	-0.9631	-2.3564
Dollar squared return ($\%^2$)	192.4877		224.8099		178.5095		214.5042	
VIX index (%)	0.0713 **		0.0797 **		0.0708 **		0.0803 **	
US TED spread (%)	0.7563		0.5158		1.0302		0.3800	
US stock market return (%)	10.0607 **		7.8375 **		10.8952 **		7.9699 **	
Japanese/European stock market return (%)	-9.2169 **		-8.9881 **		-8.4350 **		-9.0227 **	
R-squared	26.7%	11.4%	24.0%	4.2%	28.6%	15.3%	24.1%	4.2%
Adjusted R-squared	24.0%	10.2%	21.3%	2.9%	26.0%	14.1%	21.3%	3.0%
Log-likelihood	-228.6	-250.5	-232.7	-259.5	-225.5	-245.3	-232.6	-259.4
F-statistic	10.08	9.70	8.77	3.30	11.13	13.62	8.80	3.36
No of observations	231		231		231		231	

Note: This table summarises the estimation results of Eqs.(5)-(6) for the US-QE period (December 19, 2008 to May 17, 2013) using the weekly changes.
* Significance at 5% level respectively.
** Significance at 1% level respectively.

Table 5 (Continued)

Determinants of changes in 3-month 10-delta dollar-yen/euro risk reversal for the period from December 19, 2008 to May 17, 2013.

Dependent variable:	Dollar-yen risk reversal (%)		Dollar-euro risk reversal (%)			
	(E) 3-month JGB yield		(F) 10-year UST yield		(G) 10-year Bund yield	
	(II)	(I)	(II)	(I)	(II)	(I)
Dollar-yen/euro risk reversal at time *t*-1 (%)	-0.1397 *	-0.1576 *	0.0278	0.0154	0.0339	0.0158
Dollar-yen/euro risk reversal at time *t*-2 (%)	0.0737	0.0859	-0.0566	-0.0230	-0.0533	-0.0230
Constant	-0.0913	-0.0805	-0.0633	-0.0025	-0.0594	0.0049
Government bond yield (spread) (%)	-0.9801	0.6483	-0.2562	0.7947 **	0.1876	1.1277 **
Dollar squared return ($\%^2$)	217.5537		249.0841		249.1113	
VIX index (%)	0.0800 **		-0.0816 **		-0.0789 **	
US TED spread (%)	0.7923		-1.3327		-1.4724	
US stock market return (%)	7.8905 **		-3.0276		-3.3435	
Japanese/European stock market return (%)	-8.9711 **		3.6546		3.0061	
R-squared	24.0%	3.7%	28.2%	3.7%	28.1%	5.5%
Adjusted R-squared	21.3%	2.5%	25.6%	2.4%	25.5%	4.3%
Log-likelihood	-232.7	-260.0	-158.7	-192.6	-158.9	-190.4
F-statistic	8.78	2.93	10.90	2.90	10.83	4.42
No of observations	231		231		231	

Note: This table summarises the estimation results of Eqs.(5)-(6) for the US-QE period (December 19, 2008 to May 17, 2013) using the weekly changes.
* Significance at 5% level respectively.
** Significance at 1% level respectively.

Table 6

Determinants of changes in 3-month 10-delta dollar-yen risk reversal for the period from May 24, 2013 to July 29, 2016.

Dependent variable:	Dollar-yen risk reversal (%)	
	(A) 10-year UST-JGB yield spread	
	(II)	(I)
Dollar-yen risk reversal at time *t*-1 (%)	-0.0930	-0.1417
Dollar-yen risk reversal at time *t*-2 (%)	0.0554	0.0333
Constant	0.0285	0.0318
Government bond yield (spread) (%)	-0.8673	-2.3368 **
Dollar squared return ($\%^2$)	-114.7405	
VIX index (%)	0.1190 **	
US TED spread (%)	-1.4182	
US stock market return (%)	10.5147	
Japanese stock market return (%)	-7.6589 **	
R-squared	44.5%	16.7%
Adjusted R-squared	41.7%	15.2%
Log-likelihood	-110.9	-144.8
F-statistic	15.86	10.90
No of observations	167	

Note: This table summarises the estimation results of Eqs.(5)-(6) for the tapering period (May 24, 2013 to July 29, 2016) using the weekly changes.

* Significance at 5% level respectively.

** Significance at 1% level respectively.