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THE RISK OF SUDDEN DEPRECIATION OF THE EURO IN THE SOVEREIGN DEBT CRISIS OF 2009-2010

Cho-Hoi Hui and Tsz-Kin Chung

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The Risk of Sudden Depreciation of the Euro in the Sovereign Debt Crisis of 2009-2010

Cho-Hoi Hui

Hong Kong Monetary Authority

Hong Kong Institute for Monetary Research

and

Tsz-Kin Chung

Hong Kong Monetary Authority

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Abstract

The economic-political instability of a country, which is tied to its credit risk, often leads to sharp depreciation and heightened volatility in its currency. This paper shows that not only the creditworthiness of the euro-area countries with weaker fiscal positions but also that of the member countries with more sound fiscal positions are important determinants of the deep out-of-the-money euro put option prices, which embedded information on the euro crash risk during the sovereign debt crisis of 2009–2010. Using information on the option prices under the stochastic-volatility jump-diffusion model, the euro's crash probability of 11% in a year with crash size of 14% is estimated at the end of April 2010. However, during the period of the global financial crisis between the Lehman default and September 2009 before the debt crisis began, the estimated crash size reflects the potential sharp devaluation of the US dollar that might result from quantitative easing in the US.

Keywords: European Sovereign Debt Crisis, Currency Options, Credit Default Swaps, Currency Crash

JEL Classification: F31, G13

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1. Introduction

Crash risk of currencies has long been the subject of interest in international finance. Related studies, including those of Eichergreen *et al.* (1996), Frankel and Rose (1996), Kaminsky *et al.* (1998), and Kumar *et al.* (2003), use macro-economic indicators to estimate the probability of currency crashes. These studies focus on developing economies in which currency crashes are linked to their abilities to defend the currencies reflected by country-specific macro-economic variables, such as output growth, foreign exchange reserves, budget deficit, real effective exchange rate deviation, and foreign direct investment.[1] Empirical findings suggest that the strength of a currency is positively related to its economic-political stability. Increased country risk due to economic-political instability would lead investors to sell securities denominated in the country's currency and to repatriate funds, hence putting downward pressure on the currency.

The economic-political instability of a country, which is tied closely to its credit risk, often leads to depreciation and heightened volatility in its currency. Changes in the credit risk of a sovereign borrower anticipated by financial markets should be reflected in its sovereign credit default swap (CDS) spread, which is a direct measure of creditworthiness of the underlying issuer [e.g., the use of the measure in Pan and Singleton (2008)].[2] A sovereign CDS is an over-the-counter (OTC) credit protection contract in which a protection seller pays compensation to a protection buyer to make a contingent payment in the case of a pre-defined credit event. For credit protection buyers who pay a fixed fee called CDS spread, the CDS market offers the opportunity to reduce credit risk. For protection sellers, it offers the opportunity to take credit exposure and earn income without having to fund the position. Similar to CDS spreads, anticipated changes in the realised volatility of currency returns are reflected in the prices of currency options. Carr and Wu (2007) investigate the relationship between currency option-implied volatilities and sovereign creditworthiness for Mexico and Brazil from 2002–2005. They find that the level and skew of the option-implied volatility display significant co-movement with the sovereign CDS spreads of the two countries. This suggests that the currency option market has consistently set prices considering the probability of a currency crash triggered by a corresponding sovereign default of the two countries.

While the previous studies on currency crashes focused on developing countries, the onset of the European sovereign debt crisis in late 2009 called into question the grand experiment of pooling 16 countries into a monetary union. After the new Greek government took office in October 2009, the size of the deficit was revealed to be at 12.7% of the GDP in 2009, with public debts projected to rise to 135% of

[1] Currency crashes also occur in developed economies. In the early 1990s, the meltdown of the European Monetary System (EMS) led to 8% and 14% devaluations of the British pound and Italian lira when the two currencies were forced to leave the EMS. Another recent example is the dollar-yen crash in early October 1998 when the yen fell sharply by 10% in one trading day.

[2] The sovereign CDS market expanded rapidly in 2009 and 2010. The gross notion of protection is around US$2 trillion as of 2010. See the IMF's Global Financial Stability Report (Meeting New Challenges to Stability and Building a Safer System, April 2010).

the GDP by 2011. Greece's problems have laid bare the dangers of divergent fiscal policies in the euro area. Such dangers may induce economic-political events (e.g., substantial restructuring or even default of sovereign debt) and may also cause contagion to the other four members with weaker fiscal positions, namely, Portugal, Italy, Ireland, and Spain. Although the Greek economy accounts for only about 3% of the euro-area GDP, Italy and Spain are the third and fourth largest economies in the euro area, respectively. The ratio of public debt to GDP for Spain was 53% in 2009, much lower than that for Greece. Italy also has a high public debt ratio (116% in 2009), and its ratio of fiscal deficit to GDP rose to 5.3% in 2009 beyond the 3% benchmark level. Portugal and Ireland have lower public debt ratios (at 77% and 64%, respectively, in 2009).

Although Greece accounts for only 1.4% of foreign claims in European banks, economies such as Portugal, Ireland, Italy, and Spain, which have had similar fiscal problems as a whole, accounted for 15.4% in September 2009.[3] As most euro zone countries have both been creditors and debtors, any default in a country essentially causes a chain reaction among its neighbourhood. The resulting credit risk contagion is detrimental to their banks' loan portfolios and affects the stability of the European banking system. When the debt crisis worsened in the first quarter of 2010, the CDS spreads of these five debt-laden European economies notably rose. Greece's CDS spread increased the most, once surpassing 900 bps for the five-year CDS and closed at 760 bps on 28 April 2010. As concerns spread, the euro also fell sharply by about 19% as of April 2010 since November 2009 (see Figure 1). Currency traders and hedge funds reportedly bet nearly US$8 billion (€5.9 billion) against the euro, amassing the biggest ever short position since the monetary union formed.[4] The market has been eager to hedge against the risk of a crash of the euro.

This paper studies how the creditworthiness of euro-area countries affects market expectations on the stability of the euro. From the dollar-euro currency option prices and the sovereign CDS spreads of the euro-area countries from January 2006 to April 2010, we find an intriguing pattern of "correlation skew": the correlation between the option-implied volatility and sovereign CDS spreads increases monotonically as the strike prices of the options move from in-the-moneyness to out-of-the-moneyness.[5] This implies that the out-of-the-money put options on the euro are very sensitive to the sovereign credit risk in the euro area. Further analysis indicates that the sovereign credit risk is an important determinant of the prices of deep out-of-the-money dollar-euro put options after controlling for the global risk appetite, funding liquidity constraint, and macro-financial condition.

[3] The figures are from the Bank for International Settlements (BIS). European banks refer to domestically owned banks of Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, and the UK.

[4] "Traders make $8bn bet against euro," Financial Times, 8 February 2010.

[5] A dollar-euro put (call) option here is a European option of selling (buying) euro at the contractual option strike price in an exchange of US dollars at the option maturity.

Information on currency option prices has been used in recent studies on currency crashes. 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, which measures the implied volatility difference between an out-of-the-money call and an out-of-the-money put at the same (absolute) delta. Farhi *et al.* (2009) propose a disaster-based structural model in which investors incorporate a currency crash-risk premium into the value of the exchange rate. The probability of a currency crash is calibrated to implied-volatility skew using a simple jump-diffusion model. Jurek (2009) uses a non-parametric method to derive 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. However, these studies do not incorporate sovereign credit risk into their analyses and modelling frameworks of exchange rate movements.

This paper investigates whether market participants have embedded a currency-crash premium in dollar-euro options due to the sovereign credit risk in the euro area during the debt crisis. To study the quantitative significance of the premium, we employ a stochastic-volatility jump-diffusion (SVJ) option pricing model to estimate the crash risk using option prices across ranges of strikes and maturities. The SVJ model is different from the simple jump-diffusion model used by Farhi *et al.* (2009), which rules out the possibility that risk-neutral skewness can be generated by stochastic volatility. The estimated jump dynamics under the simple jump-diffusion model can thus be upwardly biased. Using the SVJ model, we explicitly estimate the dynamics of a large-amplitude with low-frequency jump conditional to the presence of stochastic volatility using the information on the entire implied-volatility surface.

This paper is structured as follows. Section 2 discusses the data and descriptive statistics. In Section 3, the interaction between the CDS market and currency option market is studied based on an econometric analysis. The estimation methodology of the probability and size of the crash risk using dollar-euro option prices is presented in Section 4. Section 5 presents the estimation results. Section 6 contains the conclusion.

2. Data Description

We obtain the daily OTC dollar-euro option prices at six fixed maturities of 1, 2, 3, 6, 9, and 12 months across five different strike prices from 2 January 2006 to 30 April 2010.[6] Option prices with different strike prices are quoted using the Black-Scholes implied volatilities in terms of at-the-money options, 10- and 25-delta risk reversals, and 10- and 25-delta butterfly spreads. A risk reversal is a directional option strategy that takes the view of the skewness of the exchange rate distribution by simultaneously buying an out-of-the-money call and selling an out-of-the-money put. A butterfly spread is a non-directional trading strategy consisted of holding an out-of-the-money call and an out-of-the-money put in which

[6] The option data are from JPMorgan Chase.

investors are benefited from a large swing in the exchange rate.[7] In the OTC currency option market, the option strikes are commonly quoted in terms of the Black-Scholes delta. The Black-Scholes delta provides a normalised measure of option moneyness where the delta of a European option increases monotonically from 0–100, with the moneyness moving from out-of-the-money to in-the-money. The total 30 market quotes of the option prices on each trading day are converted into implied volatilities of dollar-euro put options at five different strikes from 10-delta to 90-delta. Details of the conversions are provided in Appendix A.

We collect the 5-year sovereign CDS spreads of 11 countries in the euro area, namely, Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal, and Spain, with active market quotes from Bloomberg covering the period of 2 January 2006 to 30 April 2010.[8] We construct two subgroups of these 11 countries based on the relative soundness of their fiscal positions. Group A, which has more sound fiscal positions, consists of Belgium, Austria, Finland, France, Germany, and the Netherlands. Group B, which has weaker fiscal positions, consists of Greece, Ireland, Italy, Portugal, and Spain. The simple average CDS spreads of these two groups of countries are presented in Figure 1.

The upper panel in Table 1 presents the descriptive statistics for the 3-month option-implied volatilities and the average 5-year CDS spreads of the two subgroups for the full sample period. We choose the 3-month maturity as the benchmark because it conveys both short-term and long-term views of the market participants. To control the structural differences before and after the onset of the sovereign debt crisis, we split the sample period into two sub-periods. The first period is from 2 January 2006 to 31 August 2009 (middle panel, before the crisis began), and the second period is from 1 September 2009 (one month before the new government came to power after elections in Greece in October 2009) to 30 April 2010 (lower panel, the crisis period).

In the sample period before the debt crisis, the mean CDS spreads for groups A and B were 21 bps and 46 bps, respectively. The spreads surged sharply to levels of 41 bps and 147 bps in the second sample period (the debt crisis period), revealing a significant increase in sovereign risk. For the option-implied volatilities, the medians of the risk reversals at 10-delta and 25-delta were 0.17% and 0.10%, respectively, before the debt crisis period but became negative at -2.23% and -1.35%, respectively, during the crisis period. In particular, the 10-delta risk reversal reached the lowest level of -3.57% on 29 April 2010 after Standard & Poor's (S&P's) downgraded the Greek credit rating to the junk status of BB+. Between the two periods, the average at-the-money volatility changed slightly from 10.23% to 11.56%, whereas the average quotes of the corresponding butterfly spreads increased marginally from 1.11% and 0.33% to

[7] A risk reversal measures the difference between the implied volatilities of an out-of-the-money call and an out-of-the-money put. A positive (negative) risk reversal implies that the risk-neutral exchange rate distribution is positively (negatively) skewed. A butterfly spread measures the difference between the averaged implied volatility of two out-of-the-money options (a call and put) and the implied volatility of an at-the-money option. A positive butterfly spread implies that the exchange rate distribution displays a fatter tail than a lognormal distribution.

[8] There is no active sovereign CDS on Cyprus, Luxembourg, Malta, Slovakia, and Slovenia.

1.33% and 0.41%. These changes reflect the evolution of the exchange rate distribution from a Gaussian-like distribution into a negatively-skewed and fat-tailed distribution when the debt crisis began.

Table 2 reports the correlation between the weekly changes in the sovereign CDS spreads and option-implied volatilities across different strikes for the whole sample period. We use weekly sampling (Wednesday-on-Wednesday) to capture the shift of market expectations.[9] The correlation matrix across strikes and maturities shows a pattern of "correlation skew": the correlation between the CDS spreads and implied volatility increases monotonically as the option moneyness decreases. At the 3-month maturity, for example, when the option moneyness moves from 90-delta to 10-delta, the correlation between the average CDS spread of the group-B countries and implied volatility increases from 11.6% to 26.1%. The correlation analysis shows that out-of-the-money options are much more sensitive to sovereign credit risk than in-the-money options, implying a positive relationship between volatility skew and sovereign risk. The implied volatilities of the short-term options are more correlated with the CDS spreads of the group-B countries than those of the group-A countries. Nevertheless, the prices of the long-term maturity options appear to be marginally more related to the CDS spreads of the group-A countries.

3. Interaction between CDS Spreads and Currency Option Prices

We have shown the presence of interconnectivity between the sovereign CDS market and currency option market. To understand better the economic sources of such linkage, we use regression analysis to study how the market expectation of a crash of the euro anticipated in the currency option market is attributed to the sovereign credit risk of the euro-area countries. We test the following three hypotheses: (i) sovereign credit risk is an important determinant of the crash risk of the euro; (ii) the impact of sovereign credit risk on the crash risk is mainly driven by the individual euro-area countries with weaker fiscal positions; and (iii) sovereign credit risk is a separable risk factor in driving the crash risk premium after controlling other macro-financial variables.

To address these issues, we use pooled panel regression to study the relationship between implied volatility and CDS spreads of these European countries. We then include other potential determinants of the implied volatility to isolate the effect of sovereign credit risk from other macro-financial risk factors. In particular, to study the determinants of the euro crash risk, we use the 3-month 10-delta out-of-the-money implied volatility as the indicator of the crash risk. As a jump component of price dynamics mainly affects the tail behaviour of the return distribution, Collin-Dufresne *et al.* (2001), Cremers *et al.* (2008), and Cao *et al.* (2010) use out-of-the-money put options at 10-delta, which provide information beyond the 10

9 A sudden change in implied volatility, which can be driven by microstructure factors such as abrupt demand-supply imbalance and market liquidity condition, does not necessarily reflect any change in the market sentiment on the underlying distribution of the exchange rate.

percentile of the return distributions to capture the jump risk in equity prices.[10] An increase in the implied volatility is associated with a higher crash risk, both in terms of the likelihood of occurrence and the size of a jump in the exchange rate when a crash event occurs.

3.1 Two Groups of Member Countries with Sound and Weak Fiscal Positions

We first perform a pooled regression of the 10-delta implied volatility with the sovereign CDS spreads of the 11 euro-area countries as follows:[11]

$$\Delta IVOL_t = \alpha + \beta_1 \Delta CDS_{i,t} \times D_i^A + \beta_2 \Delta CDS_{i,t} \times D_i^B + v_{i,t} \qquad i = 1,2,..11 \qquad (1)$$

The explanatory variables are a panel set of the 11 countries' sovereign CDS spreads, that is, $CDS_{i,t}$ $i = 1,2,..11$. We specify the error terms as $v_{i,t} = \eta_i + \varepsilon_{i,t}$ to incorporate country fixed effects and adopt the White cross-section robust standard errors to account for the contemporaneous correlation between errors. The variables are found to be non-stationary; therefore, weekly differences are used in the regression to avoid spurious inferences.[12] The dummy variable D_i^A is defined to be 1 if $CDS_{i,t}$ refers to the group-A countries, and D_i^B equals 1 when $CDS_{i,t}$ refers to the group-B countries. The coefficients β_1 and β_2 measure the interaction between the implied volatility and sovereign CDS spreads conditional on the creditworthiness of the two groups of countries.

The estimation results with a full-sample period in Table 3a show that there is a positive relationship between weekly changes in the 10-delta implied volatility and sovereign CDS spreads. The coefficient of the group-B CDS spreads has a higher statistical significance (t-statistic = 3.21) than that of the group-A CDS spreads (t-statistic = 2.50), where 3.92% of the variation in the implied volatility is attributed to the sovereign CDS spreads in the euro area. Regarding economic significance, the coefficients indicate that 100 bp increases in the group-A and group-B country CDS spreads correspond to increases of 3.5 and 1.5 percentage points, respectively, in the 10-delta implied volatility. The economic impact of the group-A CDS spreads is stronger than that of the group-B CDS spreads in terms of absolute increases in their

[10] The risk-neutral probability of the underlying ending in-the-money is roughly equal to the delta of the option. For example, a 10-delta put option has approximately 10% probability of in-the-money at maturity. This approximation holds well for a short time to maturity.

[11] A similar specification is used by Zhang *et al.* (2009) and Cao *et al.* (2010) to investigate the linkage between CDS spreads and stock price volatility. We have also run individual regressions for the 11 euro-area countries. The results are qualitatively the same.

[12] It is noted that the reduced-form regression introduces ambiguity in interpreting causality relationship. Nevertheless, the analysis in Section 3.2 shows that sovereign risk can be viewed as an event-risk factor separable from other macro-financial factors.

CDS spreads. The estimations of the other implied volatilities show similar results in terms of coefficients and t-statistics.

The coefficients 25-delta, ATM, 75-delta, and 90-delta implied volatilities show that a 100 bp increase in the group-A CDS spreads will increase the implied volatilities by 3.0, 2.3, 1.9, and 1.7 percentage points, respectively. By comparing the increases in the 10-delta and 90-delta implied volatilities, a 100 bp increase in the group-A CDS spreads steepens the volatility skew by approximately 1.8 percentage points. The result is consistent with the correlation matrix in Table 2, where the out-of-the-money option-implied volatility is more correlated with the CDS spreads than the volatility implied by the other options. Regarding the group-B CDS spreads, a 100 bp increase in the spreads steepens the volatility skew by about 0.8 percentage points. Results in Table 4a show that the sovereign CDS spreads can explain the implied volatility skew of dollar-euro options, thus supporting the first hypothesis that sovereign credit risk is an important determinant of the euro crash risk anticipated by market participants.

Table 4b shows that in terms of the variation of the 10-delta implied volatility, the estimated coefficient of the CDS spreads of the group-A and -B countries during the debt crisis period is 0.082 and 0.011, respectively. The coefficient of the group-A CDS spreads has a higher statistical significance (t-statistic = 3.16) than that of the group-B CDS spreads (t-statistic = 2.71). This result indicates that group-A countries with more sound fiscal positions played more important roles in determining the euro crash risk than the group-B countries with weaker fiscal positions. The adjusted R-squared increases significantly to 13%. This may reflect that the currency option market considering the euro crash risk can be significantly larger when interconnectedness between group-A countries (in particular France and Germany, which are the largest economies in the euro area) and group-B countries is taken into account. Such interconnectedness appeared in the significant exposures of US$895 billion and US$704 billion of the French and German banking systems, respectively, to the group-B countries.[13] The sovereign credit risk in the group-B countries may spread to the group-A countries if the defaults of those exposures are triggered by a sovereign default of a group-B country, that is, a chain reaction.

Regression analysis shows that the sovereign CDS spreads can explain the implied volatility skew of dollar-euro options, thus supporting the first hypothesis that sovereign credit risk is an important determinant of the euro crash risk anticipated by market participants. However, results demonstrate that creditworthiness of euro-area countries with weaker fiscal positions and those with more sound fiscal positions was an important determinant of the euro crash risk during the debt crisis period. Therefore, the results do not support the second hypothesis that the impact of sovereign credit risk on the euro crash risk is mainly driven by individual euro-area countries with weaker fiscal positions.

[13] The figures are consolidated foreign claims by nationality of reporting banks (on ultimate risk basis) reported in the BIS consolidated banking statistics at the end of December 2009.

3.2 Other Economic Determinants of Implied Volatility of Currency Options

Recent research finds that sovereign credit risk interacts strongly with global and regional financial risk factors. Longstaff *et al.* (2007) show that sovereign CDS spreads are primarily driven by common factors, including the US stock and high-yield bond markets and global risk premiums, whereas Pan and Singleton (2008) find that the spreads are related to investors' risk appetite associated with global event risk, financial market volatility, and macroeconomic policy. Therefore, examining whether sovereign risk represents a separable risk factor different from other economic and financial factors in driving the euro crash risk premium is important. To address this issue, a set of macro-financial variables is included as control determinants of the 10-delta implied volatility, including the following:[14]

(i) US dollar volatility

The implied volatility of an exchange rate is essentially linked to the anticipated uncertainty on the values of both currencies in the pair. 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 (r_{USD}) as the ex-post squared return of the index.

(ii) Global risk appetite

The CBOE VIX volatility index (*VIX*), the market volatility of the US S&P 500 index, is used to gauge the global risk appetite in the financial market.[15] An increase in the VIX index is usually associated with heightened volatility across different asset classes in particular equities. Currency option-implied volatility shares commonality with the VIX index as a measure of investors' aversion to volatility exposure and hence their willingness to put capital at risk. This implies a positive relationship between the 10-delta implied volatility and VIX index.

(iii) Funding liquidity constraint

Another potential determinant of a currency crash is the sudden unwinding of carry trades. We follow Brunnermeier *et al.* (2009) and use the US dollar TED spread (*TED*), the difference between the yield of the 3-month Treasury bill and the 3-month interbank rate, to capture traders' funding liquidity constraint. When funding liquidity is tight, as reflected by a widened TED spread, traders are forced to unwind their

[14] We obtain data for these additional variables from Bloomberg.

[15] Collin-Dufresne *et al.* (2001), Cremers *et al.* (2008), and Zhang *et al.* (2009) use the VIX index as a measure of market-level volatility and find a strong relationship with firm-level credit spreads. Pan and Singleton (2008) view the VIX index as a measure of investors' risk aversion for the event risk in credit markets.

carry-trade positions and repatriate funds to US dollars as safe haven.[16] This suggests an expected negative relationship between the TED spread and the value of the euro against the dollar.

(iv) Macro-financial condition

To capture the broad changes in the macro-financial condition, we include two measures from the stock and bond markets that have been used by Collin-Dufresne *et al.* (2001), Cremers *et al.* (2008), and Cao *et al.* (2010). Regarding the stock market variables, we use the weekly returns of the S&P 500 index (*SPX*) and Dow Jones EURO STOXX 600 index (*STOXX*). The underperformance of the euro-area stock market reflects a weaker regional economic outlook relative to that in the US and puts downward pressure on the euro. For the bond market variables, we use the term spreads between 10-year and 2-year yields of the US Treasuries (*USTerm*) and euro-area government bonds (*EUTerm*).[17] Collin-Dufresne *et al.* (2001) interpret the term spread (i.e., the slope of a yield curve) as a proxy for the overall state of an economy, as well as a measure of expected future short rates. An upward sloping yield curve indicates future economic growth, whereas a flattening yield curve reflects a poor economic prospect, often as a result of "flight-to-quality" that pushes the long-term yield down. Therefore, the term spread of a country's government bonds is expected to be negatively related to the strength of its currency.

After incorporating all these control variables into Eq. (1), the regression becomes

$$\begin{aligned}\Delta IVOL_t &= \alpha + \beta_1 \Delta CDS_{i,t} \times D_t^A + \beta_2 \Delta CDS_{i,t} \times D_t^B \\ &+ \beta_3 \Delta r_{USD,t}^2 + \beta_4 \Delta VIX_t + \beta_5 \Delta TED_t \\ &+ \beta_6 \Delta SPX_t + \beta_7 \Delta USTerm_t + \beta_8 \Delta STOXX_t + \beta_9 \Delta EUTerm_t + v_{i,t}\end{aligned} \quad (2)$$

We use the different specifications of Eq. (2) to isolate the potential effects of multicollinearity. As shown in Table 4a, the pooled panel regression can explain the 32% variation of the implied volatility. The stock market returns (significant) and term spreads (insignificant) show the expected signs and explain another 8.3% of the adjusted R-squared, indicating that these macro-financial factors are important determinants of the euro crash risk. The VIX index explains an additional 3.1% of the implied volatility; however, it is only marginally significant. A possible explanation is that assessing the risk aversion in the foreign exchange market using the stock market volatility is prone to a measurement error as the two markets may not be perfectly linked. The change in the ex-post US dollar volatility contributes a significant portion of 16.7%, suggesting the importance of controlling the US dollar factor. The impact of the TED spreads

16 We take the US dollar as the funding currency because the interest rate of the US dollar has been lower than that of the euro since mid-2007.

17 The euro government bond yields are generic yields constructed by Bloomberg based on the benchmark government bonds of Germany, France, and Spain.

(funding liquidity constraint) is not significant, which may reflect that the dollar-euro was not a major carry trade pair during the sample period.

Regarding the sovereign risk variables, the explanatory power of the CDS spreads is partially driven out by the set of additional variables. The t-statistics of the group-A and group-B CDS spreads shrink from 2.50 and 3.21 using Eq. (1) to 1.31 and 1.87 using Eq. (2), respectively. The significance of the group-B CDS spreads is robust under the alternative specifications and remains significant at the 10% confidence level. The result supports the hypothesis that the sovereign credit risk is a separable risk factor in driving the euro crash risk premium after controlling other macro-financial variables. Conversely, the effects of the group-A CDS spreads fade out when the stock market returns and the term spreads are included. This shows that group-A CDS spreads share common characteristics with other macro-financial factors in explaining the euro crash risk.

Focusing on the sub-sample period of the sovereign debt crisis, we expect the effects of the sovereign risk to be more prominent.[18] As shown in Table 4b, the explanatory power of the CDS spreads markedly increases to 13.0%, indicating that sovereign risk was a primary driver of the crash risk during the debt crisis. Regarding the control variables, the macro-financial factors and global risk appetite exhibit higher economic and statistical significance: the stock market returns, term spreads, and VIX index altogether explain about 36.9% of the implied volatility variation. However, this is not the case with the US dollar volatility, reflecting that the surge in the dollar-euro implied volatility was not related to the actual fluctuation in the dollar value. The effects of the sovereign risk persisted despite the inclusion of the control variables. We relate this finding to a “peso problem”: both a currency crash and sovereign default fall into the category of rare events, which, once occurring, lead to a large drop in asset prices and aggregate consumption.[19] In the context of asset pricing, this implies that investors require a distinct type of risk premium associated with these rare events in a way different from other economic/financial factors [see Liu *et al.* (2005), Jurek (2009), and Fahri *et al.* (2009)].

The estimation result in the debt crisis period shows that the effect of the group-B CDS spreads on the 10-delta implied volatility was subsumed by that of the group-A CDS spreads with higher t-statistics. This is consistent with finding in the previous subsection that not only the creditworthiness of the euro-area countries with weaker fiscal positions but also that of member countries with more sound fiscal positions were important determinants of the euro crash risk during the crisis period.

In summary, empirical results show that the sovereign credit risk was an important determinant of the euro crash risk, distinct from other macro-financial factors. Furthermore, the crash risk was not only

18 The estimation results for the sub-sample period before the debt crisis are similar to those of the full-sample period.

19 The term “peso problem” as defined by Cochrane (2001), which is “a generic term for the effects of small probabilities of large events on empirical work,” is used here.

exposed to the credit creditworthiness of countries with weaker fiscal positions but also to those with more sound fiscal positions.

4. Estimations of Currency Crash Risk from Option Prices

Empirical findings provide evidence that a risk premium associated with the possibility of a euro crash due to sovereign risk is embedded in the pricing of the out-of-the-money euro put options. Option markets have the desirable property of being forward-looking in nature and are thus useful sources of information for gauging market sentiments about future values of financial assets, including exchange rates. Options, whose payoff depends on a limited range of the expected exchange rate, offer broad information about market expectations. In particular, potential extreme movements of the exchange rate can be inferred from out-of-the-money option prices. In this section and the next, we study the quantitative significance of the crash risk using an SVJ option pricing model based on option prices across ranges of strikes and maturities. This choice of exchange rate dynamics is relevant to assessing euro crash risk because the expected jump of the underlying exchange rate as well as its probability can then be recovered from such a specification. The estimated crash risk in terms of jump probabilities and size can provide information about when the corresponding crash risk is significant during the sample period.

Several studies have used option prices to estimate the risk of a market crash. Using futures option prices of the S&P 500 index, Bates (1991) estimates a jump-diffusion model and finds that the option market conveys forward-looking information about the October 1987 stock market crash. In recent studies, Pan (2002) finds that the jump risk premium reconciles the time-series behaviour of the S&P 500 index with the cross-sectional pattern of option prices. Liu *et al.* (2005) develop an equilibrium model, which incorporates jumps into aggregate endowment, and argue that index options' skew can be explained by the jump-risk premium compensated for a rare event. Bakshi *et al.* (1997) illustrate that the SVJ model provides a parsimonious fit to stock option prices for both short-term and long-term maturities.[20] In the context of foreign exchanges, Bates (1996) concludes that the SVJ model provides a consistent description of cross-sectional option prices as well as the time-series properties of the deutsche mark exchange rate.

In view of these theoretical and empirical findings, we assume the risk-neutral dollar-euro exchange rate dynamics to follow the SVJ model as follows:

$$\begin{aligned} \frac{dS}{S} &= \left(r_d - r_f - \lambda m\right)dt + \sqrt{v}\,dW_s + \left[e^q - 1\right]dN \\ dv &= \kappa(\theta - v)dt + \eta\sqrt{v}\,dW_v \end{aligned} \qquad (3)$$

[20] The SVJ model is commonly used by market participants to model the volatility surface [see Sepp (2003) and Gatheral (2006)].

where S is the value of the US dollar per euro, r_d is the US dollar interest rate, r_f is the euro interest rate, and ν is the instantaneous stochastic volatility.[21] The instantaneous volatility ν is assumed to follow a square-root process with a mean-reversion level θ, mean-reversion speed κ, and volatility of volatility η. The correlation between the exchange rate and instantaneous volatility is specified as $dW_s dW_\nu = \rho dt$, where a negative correlation implies a negative skewness of the exchange rate distribution. A large negative jump is used to capture the currency crash risk triggered by a sovereign default. The jump is modelled by a Poisson process dN with intensity λ, where the jump size is assumed to be lognormally distributed such that $q \sim N(\mu,\sigma)$. Under this setting, the probability of one jump in a time interval dt is given by λdt, and the expected jump size is $m = E^Q\left[e^q - 1\right]$, where Q denotes the risk-neutral probability measure. The SVJ model provides a rich structure to model the skewness and kurtosis of the risk-neutral distributions implied from the volatility surface.

The price of a European call option $C(S,\nu,\tau)$ under the SVJ model in Eq. (3) can be obtained using the following closed-form solution (see Appendix B):

$$C(S,\nu,\tau) = C(Ke^x,\nu,\tau) = K\left[e^{-r_f\tau}e^x P_1(x,\nu,\tau) - e^{-r_d\tau}P_2(x,\nu,\tau)\right] \tag{4}$$

where τ is the maturity time, K is the strike, $x = \ln(S/K)$, and

$$P_j(x,\nu,\tau) = \frac{1}{2} + \frac{1}{\pi}\int_0^\infty d\omega \,\mathrm{Re}\left[\frac{\Phi_j(x,\nu,\tau,\omega)}{i\omega}\right] \qquad j = 1,2 \tag{5}$$

with

$$\Phi_j(x,\nu,\tau;\omega) = \exp\left[C_j(\omega,\tau) + D_j(\omega,\tau)\nu + J_j(\omega,\tau) + i\omega x\right]$$

$$C_j(\omega,\tau) = i\mu\omega\tau + \kappa\theta\left\{r_{j,-} - \frac{1}{a}\ln\left[\frac{1-g_j e^{-d_j\tau}}{1-g_j}\right]\right\}$$

[21] The interest rates are LIBORs obtained from Bloomberg.

$$D_j(\omega,\tau) = r_{j,-}\frac{1-e^{-d_j\tau}}{1-\frac{r_{j,-}}{r_{j,+}}e^{-d_j\tau}}$$

$$J_j(\omega,\tau) = -\lambda\tau(i\omega+\delta_j)\left\{\exp\left[\mu+\frac{1}{2}\sigma^2\right]-1\right\}+$$
$$\lambda\tau\left\{\exp\left[\mu(\delta_j+i\omega)+\frac{1}{2}\sigma^2(\delta_j+i\omega)^2\right]-1\right\}$$

and

$$a=\frac{1}{2}\eta^2,\quad b_j = i\omega\rho\eta-\kappa+\delta_j\rho\eta,\quad c_j=\left(\delta_j-\frac{1}{2}\right)i\omega-\frac{1}{2}\omega^2,$$
$$r_{j,\pm}=\frac{-b_j\pm d_j}{2a},\quad d_j=\sqrt{b_j^2-4ac_j},\quad g_j=\frac{r_{j,-}}{r_{j,+}},\quad \delta_j=\begin{cases}1, & j=1\\ 0, & j=2\end{cases}$$

Here, i denotes the imaginary number, and $\mathrm{Re}[\bullet]$ stands for the real part of a complex number. The option price can be easily obtained using the numerical integration of Eq. (5). The corresponding put option price can be derived using put-call parity.

The market implied volatilities are converted into option prices in terms of five different strikes (i.e., 10-, 25-, 50-, 75-, and 90-delta) at six fixed maturities of 1, 2, 3, 6, 9, and 12 months using standard Black-Scholes formula.[22] To recover risk-neutral dynamics, the model is calibrated to observed option prices for each trading day by searching a set of parameters $\Theta=(\rho,\kappa,\theta,\eta,\nu,\lambda,\mu,\sigma)$ that minimise the daily sum-of-square pricing error:

$$\min_{\Theta}\left\{\sum_{j=1}^{n}\sum_{i=1}^{m}w_{ij}\left(C_{\text{model}}^{ij}-C_{\text{market}}^{ij}\right)^2+\alpha g(\Theta)\right\} \tag{6}$$

where, i and j denote the i^{th} strike for the j^{th} maturity, w_{ij} is the weighting function,

[22] The delta is a measure of a change in the option price with respect to a small change in the underlying price.

$g(\Theta)=\|\Theta-\Theta_0\|^2$ is the penalty function, and Θ_0 is the initial estimate.[23] We choose the weighting function to be the inverse of the Black-Scholes vega because this effectively rescales the option pricing errors into the errors in the implied volatility, as suggested in Christoffersen *et al.* (2009).[24]

We adopt the following procedure to ensure the reliability of the parameters. First, we estimate a nested simple stochastic volatility model, such that only five parameters $\Theta=(\rho,\kappa,\theta,\eta,\nu)$ are estimated. The option prices at medium-term to long-term maturities (6-month to 12-month) can be fitted using the nested stochastic volatility model. The estimates are not sensitive to the initial guess. We then estimate the full SVJ model using the estimation results of the stochastic volatility model as the initial estimates. This two-stage procedure reduces the optimisation time.

In the second stage, we encounter an identification problem in gauging the jump parameters (λ,μ,σ). We find that long-term options are very inert to jump dynamics. The calibration appears to be biased towards the dominance of stochastic volatility when the entire volatility surface is fed into the calibration algorithm. This is consistent with the finding by Das and Sundaram (1999) that implied-volatility skew generated by jump diffusion dies out for time horizons longer than three months. This means that long-term volatility smiles contain little information on exchange rate jumps. To pursue robust parameter identification, we re-calibrate the model using the short-term options (i.e., 1-month to 3-month maturities) only. Price information of the long-term options is thus used for controlling the role of stochastic volatility, whereas that of the short-term options is used for gauging jump dynamics. In effect, the stochastic volatility parameters $\Theta=(\rho,\kappa,\theta,\eta,\nu)$ are qualitatively the same when the model is re-calibrated using only the short-term options.

5. Euro Crash Risk in the Sovereign Debt Crisis

The estimated crash probability (λ), expected crash size (μ), and its standard deviations (σ) under the SVJ model in Eq. (3) are used to gauge how market participants anticipate the euro crash risk. The estimated model parameters based on the calibration to daily cross-sectional option prices are shown in Figures 2 and 3. Figure 2 shows noticeable co-movement between the estimated crash probability in a one-year horizon and the group-A and -B sovereign CDS spreads after the Lehman default in September 2008, in particular, during the sovereign debt crisis from October 2009 to April 2010. The movement of

[23] Calibrations of the class of stochastic volatility and jump-diffusion models suffer from parameter instability because the calibrations are mathematically ill-posed in nature [see Hamida and Cont (2005)]. The penalty function effectively transforms the calibration problem from an ill-posed problem to a regularised problem. However, such an optimisation can bring about local minima. One has to try different initial sets of parameters to achieve global minimisation. An efficient way to seek reasonable initial estimates is to resort to the short-expiration asymptotical expression of the option prices to match the short-term volatility skew. See Gatheral (2006) for the discussion on this issue.

[24] The vega is a measure of change in the option price with respect to a small change of the volatility of the underlying price.

the estimated crash probability is consistent with the empirical findings in Section 3 that the euro crash risk, which is represented by the 10-delta implied volatility, is driven by the sovereign credit risk in the euro area.

Figure 3 shows that the expected crash size was not statistically different from zero as measured by the standard deviation of the jump size during the period between the Lehman default in September 2008 and March 2009. Therefore, the actual crash risk anticipated in the currency option market was not clear and might not be material according to the SVJ model specification. This reflects that although the sovereign credit risk affected the 10-delta euro put prices during the period, the effect on the option prices did not appear to be quantitatively significant as crash risk. This finding indicates that the euro crash might not be a concern in the currency option market during the global financial crisis after the Lehman default when the euro fell sharply against the US dollar (see Figure 1). This is also consistent with the view that the debt crisis in the euro area should not be attributed to the global financial crisis, although the latter has led to deterioration in fiscal positions in some European economies. After the collapse of Lehman Brothers, Greece could still finance its borrowing easily because its banks were relatively free of the toxic mortgage securities.

Between March and September 2009, with the crash probability at the 6% level, the corresponding crash size increased to about 10% in May 2009 and remained positive. The crash size indicates that the currency option market might have anticipated a crash of the US dollar when the Federal Reserve adopted quantitative easing in March 2009 to help counter the adverse effects of the financial crisis on the US economy. This included additional stimulus through its purchases of agency securities and longer-term Treasury securities. The concern about potential sharp devaluation of the US dollar that might result from this quantitative easing is reflected from the estimated crash probability and size during the period.

Following the onset of the debt crisis, the estimated crash probability of the euro has climbed since October 2009 when the expected crash size turned from positive to negative. The crash size, which was statistically different from zero, reached the negative level of -12.5% on 16 December 2009 when Greece's credit downgrades were downgraded by Fitch, Moody's, and S&P's to BBB+, A2, and BBB+, respectively. The corresponding standard deviation of the jump size was around 9%, indicating the significant uncertainty on the future path of the dollar-euro exchange rate. The 0.08 crash probability in late December 2009 is consistent with the 0.05 default probability of Greece implied from its CDS spread of 280 bps.[25] According to the SVJ model, the currency option market has set prices in anticipation of a euro crash that can be triggered by a sovereign default of Greece.

[25] Implied default intensity (λ_{CDS}) from the sovereign CDS spread (S) is estimated by the relationship

$$\lambda_{CDS} = \frac{s}{1-w}$$

where, W is the recovery rate of the sovereign debt. We assume both quantities to be constant and take the recovery rate to be 0.4.

The sovereign debt problems in Greece, Portugal, and Spain intensified in the first four months of 2010 when their CDS spreads surged to the unprecedented levels of 428 bps, 244 bps, and 173 bps, respectively, on 8 February 2010. What began as a peripheral country's fiscal woe turned into a region-wide sovereign debt crisis. On 15 February 2010, in response to Germany's opposition to the proposal of a quick bailout of Greece, the option-implied crash probability rose to 9.4% with the expected crash size of -10.6%. The market condition eased somewhat when the Greek parliament passed austerity measures to cut the budget deficit. In March 2010, the Greek CDS spread narrowed to 300 bps, whereas the crash probability and expected crash size decreased to about 0.07 and -5%, respectively.

The market condition further worsened when Moody's downgraded Greece by one notch on 22 April 2010. The Greek CDS spread quickly rose to the level of 644 bps despite the activation of the 45 billion euro loan package offered by the IMF. When S&P's downgraded the Greek credit rating to the junk status of BB+, and the Greek CDS spread widened by 150 bps to 794 bps on 27 April 2010. The average CDS spread of the group-A countries also rose from 30 bps to 58 bps in April 2010. Consequently, the crash probability increased to 11%, with an expected crash size of -14% at the end of April 2010.

6. Conclusion

The economic-political instability of a country, which is tied closely to its credit risk, often leads to depreciation and heightened volatility in its currency. This paper shows that the creditworthiness of euro-area countries can affect market expectations on the stability of the euro. Based on the dollar-euro currency option prices and the sovereign CDS spreads of the euro-area countries from January 2006 to April 2010, we find that the correlation between the option-implied volatility and sovereign CDS spread increases monotonically as the strike prices of the options move from in-the-moneyness to out-of-the-moneyness. The analysis indicates that not only the creditworthiness of the euro-area countries with weaker fiscal positions but also that of member countries with more sound fiscal positions are important determinants of the prices of deep out-of-the-money euro put options after controlling for global risk appetite, funding liquidity constraint, and macro-financial condition.

We estimate the dynamics of a large-amplitude with low-frequency jump of the euro exchange rate conditional to the presence of stochastic volatility using information on the entire volatility surface implied from dollar-euro option prices under the SVJ model. The estimated jump probability and size, which reflect the currency crash risk, indicate that market participants embedded a currency-crash premium in the dollar-euro options due to the sovereign credit risk in the euro area during the sovereign debt crisis. The euro's crash probability of 11% in a year with crash size of 14% is estimated at the end of April 2010. However, the estimated crash size was not statistically different from zero during the period between the Lehman default and March 2009. This shows that the euro crash might not be a concern in the currency option market during the global financial crisis after the Lehman default when the euro fell sharply against the US dollar. In addition, the estimated positive crash size between March and September 2009 before the debt crisis indicates that the market was concerned with the potential sharp devaluation of the US dollar that might result from the quantitative easing in the US.

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Table 1. Descriptive Statistics for Option-Implied Volatilities and CDS Spreads

	At-the-money volatility	10-delta risk reversal	25-delta risk reversal	10-delta butterfly spread	25-delta butterfly spread	CDS spread - Group A	CDS spread - Group B
a.) From January 2006 to April 2010							
Mean	10.43	-0.32	-0.19	1.15	0.34	23.73	61.61
Median	9.37	0.00	0.00	1.02	0.29	9.67	30.60
Maximum	25.16	1.73	1.02	3.35	1.00	138.33	346.80
Minimum	5.03	-4.68	-2.75	0.41	0.12	1.83	4.25
Std. Dev.	4.14	1.08	0.64	0.73	0.22	28.69	67.86
Skewness	1.22	-1.01	-1.02	1.37	1.38	1.59	1.09
Kurtosis	4.17	3.35	3.36	4.36	4.35	5.32	3.24
No. of obs.	1129	1129	1129	1129	1129	1129	1129
b.) From January 2006 to August 2009							
Mean	10.23	-0.05	-0.03	1.11	0.33	20.65	46.11
Median	8.84	0.17	0.10	0.94	0.28	4.00	10.00
Maximum	25.16	1.73	1.02	3.35	1.00	138.33	241.60
Minimum	5.03	-4.68	-2.75	0.41	0.12	1.83	4.25
Std. Dev.	4.46	0.82	0.48	0.78	0.23	29.97	58.19
Skewness	1.29	-1.26	-1.26	1.42	1.47	1.90	1.49
Kurtosis	3.87	5.86	5.88	4.13	4.20	5.94	4.09
No. of obs.	955	955	955	955	955	955	955
c.) From September 2009 to April 2010							
Mean	11.56	-1.80	-1.07	1.33	0.41	40.64	146.64
Median	11.58	-2.23	-1.35	1.25	0.38	39.50	142.50
Maximum	13.39	0.68	0.40	1.75	0.53	63.17	346.80
Minimum	10.21	-3.57	-2.10	1.04	0.33	28.17	87.20
Std. Dev.	0.64	1.13	0.67	0.24	0.07	8.55	52.45
Skewness	0.09	0.97	0.98	0.55	0.62	0.63	1.14
Kurtosis	2.61	2.55	2.52	1.86	1.93	2.57	4.66
No. of obs.	174	174	174	174	174	174	174

Note: The implied volatility figures are in terms of percentage while the CDS spreads are in basis points.

Table 2. Correlation between Option-Implied Volatilities and CDS Spreads

Sample Period: 2 January 2006 to 30 April 2010

	10-delta OTM	25-delta OTM	ATM	75-delta ITM	90-delta ITM
Group-A counties					
1-month	20.4%	18.6%	15.2%	12.3%	10.9%
2-month	23.2%	21.3%	17.5%	14.0%	12.3%
3-month	24.9%	22.3%	18.1%	14.2%	11.9%
6-month	29.2%	26.3%	21.4%	16.6%	13.8%
9-month	30.9%	28.2%	23.2%	18.1%	15.0%
12-month	31.0%	28.5%	23.7%	18.6%	15.4%
Group-B countries					
1-month	23.3%	21.2%	17.2%	13.4%	11.4%
2-month	26.3%	24.2%	19.6%	15.1%	12.7%
3-month	26.1%	23.5%	19.0%	14.4%	11.6%
6-month	28.7%	26.0%	20.8%	15.4%	12.0%
9-month	29.8%	27.5%	22.3%	16.7%	13.1%
12-month	29.6%	27.7%	22.9%	17.4%	13.7%

Notes:

1.) OTM = out-of-the-money dollar-euro put; ATM = at-the-money dollar-euro put; ITM = in-the-money dollar-euro put

2.) We express the strike of the implied volatility in terms of the delta of a dollar-euro put. By put-call parity, the implied volatility of an ITM put equals that of an OTM call with the same strike. For example, the implied volatility of a 90-delta ITM put is the same as that of a 10-delta OTM call.

Table 3a. Determinants of 3-Month Implied Volatilities across Different Strikes from January 2006 to April 2010

	10-delta	25-delta	ATM	75-delta	90-delta
Constant	0.011	0.008	0.003	0.000	-0.001
	(0.14)	(0.04)	(0.04)	(0.00)	-(0.01)
CDS spread (Group-A, in bps)	0.035**	0.030**	0.023*	0.019	0.017
	(2.50)	(2.25)	(1.83)	(1.43)	(1.21)
CDS spread (Group-B, in bps)	0.015***	0.013***	0.010**	0.008*	0.007
	(3.21)	(2.87)	(2.27)	(1.70)	(1.35)
R-squared	4.49%	3.61%	2.36%	1.41%	0.96%
Adj. R-squared	3.92%	3.04%	1.78%	0.82%	0.37%
F-statistic	7.90	6.30	4.06	2.39	1.62
Total no. of obs.	2029				
No. of countries	11				

Notes:
1.) The t-statistics (in parentheses) are computed from the White cross-sectional standard errors.
2.) *, ** and *** indicate significant at 10%, 5% and 1% levels respectively.

Table 3b. Determinants of 3-Month Implied Volatilities across Different Strikes from September 2009 to April 2010

	10-delta	25-delta	ATM	75-delta	90-delta
Constant	0.013	-0.001	-0.026	-0.053	-0.073
	(0.10)	-(0.25)	-(0.25)	-(0.53)	-(0.70)
CDS spread (Group-A, in bps)	0.082***	0.073***	0.063***	0.054***	0.050***
	(3.16)	(3.33)	(3.48)	(3.47)	(3.29)
CDS spread (Group-B, in bps)	0.011***	0.010***	0.009***	0.008***	0.007***
	(2.71)	(3.12)	(3.54)	(3.65)	(3.36)
R-squared	15.8%	16.5%	15.8%	13.4%	11.2%
Adj. R-squared	13.0%	13.8%	13.0%	10.6%	8.3%
F-statistic	5.80	6.14	5.80	4.80	3.89
Total no. of obs.	385				
No. of countries	11				

Notes:
1.) The t-statistics (in parentheses) are computed from the White cross-sectional standard errors.
2.) *, ** and *** indicate significant at 10%, 5% and 1% levels respectively.

Table 4a. Determinants of 3-Month 10-Delta Implied Volatility of Dollar-Euro Options from January 2006 to April 2010

	(IV)	(III)	(II)	(I)
Constant	-0.011	0.012	0.011	0.011
	(-0.18)	(0.18)	(0.15)	(0.14)
CDS spread (Group-A, in bps)	0.018	0.028**	0.034***	0.035***
	(1.31)	(1.85)	(2.39)	(2.50)
CDS spread (Group-B, in bps)	0.0084**	0.0128***	0.015***	0.015***
	(1.87)	(2.58)	(3.51)	(3.21)
Dollar squared return ($\%^2$)	0.055***	0.065***	0.065***	
	(2.97)	(3.42)	(3.60)	
VIX index (%)	0.072	0.055		
	(1.42)	(1.19)		
US TED spread (bps)	-0.003	-0.001		
	(-0.79)	(-0.20)		
Macro-financial variables				
US term spread (bps)	-0.0002			
	(-0.02)			
US stock market return (%)	0.181**			
	(2.16)			
EU term spread (bps)	0.012			
	(1.02)			
EU stock market return (%)	-0.163***			
	(-3.46)			
R-squared	32.6%	24.3%	21.2%	4.5%
Adjusted R-squared	32.0%	23.7%	20.6%	3.9%
Log likelihood	-2674.8	-2792.8	-2833.3	-3037.8
F-statistic	50.91	42.74	41.36	7.90
Total no. of obs.	2029			
No. of countries	11			

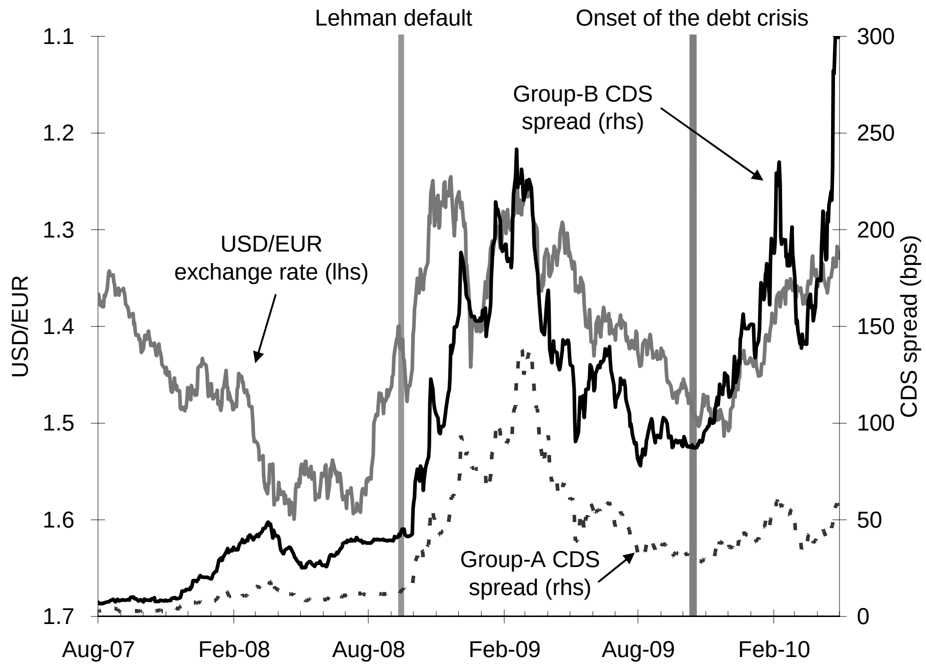
Notes:
1.) The t-statistics (in parentheses) are computed from the White cross-sectional standard errors.
2.) *, ** and *** indicate significant at 10%, 5% and 1% levels respectively.

Table 4b. Determinants of 3-Month 10-Delta Implied Volatility of Dollar-Euro Options from September 2009 to April 2010

	(IV)	(III)	(II)	(I)
Constant	-0.037	0.054	0.013	0.013
	(-0.36)	(0.49)	(0.10)	(0.10)
CDS spread (Group-A, in bps)	0.041***	0.047***	0.074***	0.082***
	(2.70)	(3.11)	(3.02)	(3.16)
CDS spread (Group-B, in bps)	0.0039*	0.0061**	0.010***	0.011***
	(1.70)	(2.15)	(2.47)	(2.71)
Dollar squared return ($\%^2$)	0.053	0.092**	0.091**	
	(1.12)	(2.04)	(1.98)	
VIX index (%)	0.231**	0.178***		
	(2.30)	(4.13)		
US TED spread (bps)	-0.037	0.005		
	(-0.69)	(0.10)		
Macro-financial variables				
US term spread (bps)	0.0375**			
	(2.02)			
US stock market return (%)	0.225**			
	(1.95)			
EU term spread (bps)	-0.029*			
	(-1.66)			
EU stock market return (%)	-0.152			
	(-1.21)			
R-squared	52.4%	42.2%	20.6%	15.8%
Adjusted R-squared	49.9%	39.9%	17.9%	13.0%
Log likelihood	-352.5	-389.7	-450.8	-462.3
F-statistic	21.12	17.97	7.43	5.80
Total no. of obs.	385			
No. of countries	11			

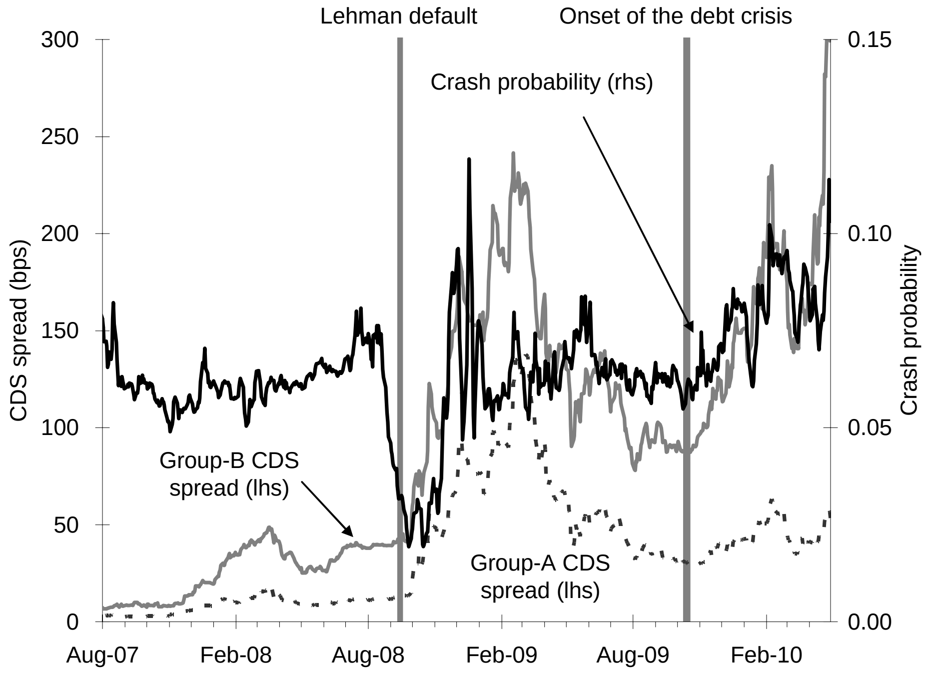
Notes:
1.) The t-statistics (in parentheses) are computed from the White cross-sectional standard errors.
2.) *, ** and *** indicate significant at 10%, 5% and 1% levels respectively.

Figure 1. Sovereign CDS Spreads and Dollar-Euro Exchange Rate



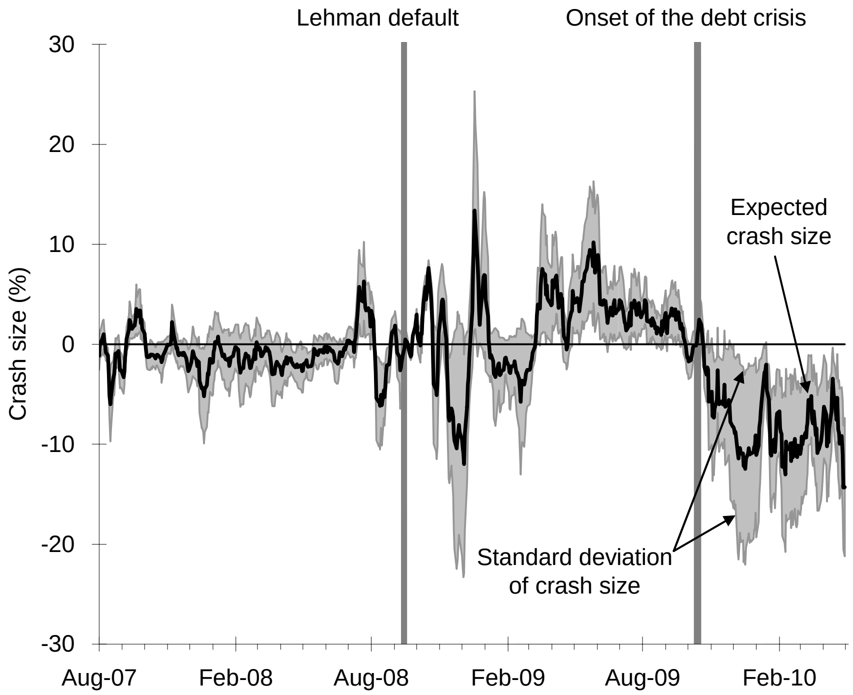
Note: The group-A CDS spread is the average of CDS spreads of Belgium, Austria, Finland, France, Germany and the Netherlands. The group-B CDS spread is the average of CDS spreads of Greece, Portugal, Spain, Ireland and Italy. The default of Lehman Brothers and onset of the sovereign debt crisis are marked at 15 September 2008 and 14 October 2009 respectively.

Figure 2. Crash Probability (λ) of Euro Crash Risk under SVJ Model



Note: The group-A CDS spread is the average of CDS spreads of Belgium, Austria, Finland, France, Germany and the Netherlands. The group-B CDS spread is the average of CDS spreads of Greece, Portugal, Spain, Ireland and Italy. The default of Lehman Brothers and onset of the sovereign debt crisis are marked at 15 September 2008 and 14 October 2009 respectively.

Figure 3. Expected Crash Size (μ) and Standard Deviation of Crash Size (σ) of Euro Crash Risk under SVJ Model



Note: The default of Lehman Brothers and onset of the sovereign debt crisis are marked at 15 September 2008 and 14 October 2009 respectively.

Appendix A

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

$$\Delta_{call} = e^{-q\tau} N(d_1), \quad \Delta_{put} = -e^{-q\tau} N(-d_1), \quad d_1 = \frac{\ln\left(\frac{Se^{(r-q)\tau}}{K}\right) + \frac{1}{2}\sigma_{imp}^2 \tau}{\sigma_{imp}\sqrt{\tau}} \tag{A1}$$

where σ_{imp} is the implied volatility. Other variables are defined in Section 4. The definitions of the market quotes of currency options are as follows:

- Delta-neutral straddle: A delta-neutral position consists of a long call and a long put where the deltas of the call and put are the same. The strike is determined such that $\Delta_{call} = \Delta_{put}$, that is, $d_1 = 0$. This is the at-the-money implied volatility quoted in the OTC currency option market.
- Risk reversal is quoted as the difference in the implied volatilities of an out-of-the-money call and an out-of-the-money put. Mathematically, the 10-delta and 25-delta risk reversals are given by

$$\begin{aligned} rr10 &= IV(\Delta_{call} = 10) - IV(\Delta_{put} = 10) \\ rr25 &= IV(\Delta_{call} = 25) - IV(\Delta_{put} = 25) \end{aligned} \tag{A2}$$

  where $IV(\Delta_{put} = x)$ and $IV(\Delta_{call} = x)$ denote the implied volatilities of the put and call with x-delta.
- Butterfly spread is quoted as the average difference in the implied volatility of an out-of-the-money call and put with that of a delta-neutral straddle. The 10-delta and 25-delta butterfly spreads are given by

$$\begin{aligned} bf10 &= \left[IV(\Delta_{call} = 10) + IV(\Delta_{put} = 10)\right]/2 - IV(str) \\ bf25 &= \left[IV(\Delta_{call} = 25) + IV(\Delta_{put} = 25)\right]/2 - IV(str) \end{aligned} \tag{A3}$$

where $IV(str)$ is the delta-neutral straddle implied volatility. The implied volatilities at different strikes (deltas) can then be recovered using Eqs. (A2) and (A3).

Appendix B

By Ito's lemma, the price of a European call option under the SVJ model in Eq. (3) can be shown to satisfy the Kolmogorov backward equation

$$\begin{aligned}\frac{\partial C(S,\nu,\tau)}{\partial\tau} &= \left[\frac{1}{2}\nu S^2\frac{\partial^2}{\partial S^2}+\rho\nu\eta S\frac{\partial^2}{\partial\nu\partial S}+\frac{1}{2}\eta\nu^2\frac{\partial^2}{\partial\nu^2}\right.\\ &\quad\left.+\left(r_d-r_f-\lambda m\right)S\frac{\partial}{\partial S}+\kappa(\theta-\nu)\frac{\partial}{\partial\nu}-r\right]C(S,\nu,\tau)\\ &\quad+\lambda E^Q\left[C\left(Se^q,\nu,\tau\right)-C(S,\nu,\tau)\right]\end{aligned} \tag{B1}$$

subject to the terminal boundary condition $C(S,\nu,\tau=0)=\max[S-K,0]$. Following Duffie *et al.* (2002), we perform the change of variable $x=\ln(S/K)$ and assume the solution form as follows:

$$\begin{aligned}C(S,\nu,\tau) &= C\left(Ke^x,\nu,\tau\right)\\ &= K\left[e^{-r_f\tau}e^xP_1(x,\nu,\tau)-e^{-r_d\tau}P_2(x,\nu,\tau)\right]\end{aligned} \tag{B2}$$

where $P_1(x,\nu,\tau)$ and $P_2(x,\nu,\tau)$ are related to the probabilities of a call option that expires in-the-money (with $S>K$) and out-of-the-money (with $S<K$), respectively. By direct substitution, showing that the probabilities $P_j(x,\nu,\tau)$ satisfy the following partial integro-differential equations (PIDEs) is not difficult:

$$\begin{aligned}\frac{\partial P_j(x,\nu,\tau)}{\partial\tau} &= \left[\frac{1}{2}\nu\frac{\partial^2}{\partial x^2}+\rho\nu\eta\frac{\partial^2}{\partial\nu\partial x}+\frac{1}{2}\eta^2\nu\frac{\partial^2}{\partial\nu^2}\right.\\ &\quad\left.+\left(\mu+\beta_j\nu\right)\frac{\partial}{\partial x}+\left[\alpha+\theta_j\nu\right]\frac{\partial}{\partial\nu}+\delta_j m\right]P_j(x,\nu,\tau)\\ &\quad+\lambda E^Q\left[P_j\left(Ke^{q+x},\nu,\tau\right)-P_j(x,\nu,\tau)\right]\end{aligned} \tag{B3}$$

for $j=1,2$, where

$$\begin{aligned}&\mu=r_d-r_f-\lambda m,\quad \alpha=\kappa\theta,\\ &\beta_j=-\frac{1}{2}+\delta_j,\quad \theta_j=-\kappa\nu+\delta\rho\eta\nu,\quad \delta_j=\begin{cases}1, & j=1\\ 0, & j=2\end{cases}\end{aligned} \tag{B4}$$

with the boundary conditions

$$P_1(x,\nu,\tau=0)=\begin{cases}1 & ,x>\ln(S/K)\\ 0 & ,x\le\ln(S/K)\end{cases}$$
$$P_2(x,\nu,\tau=0)=\begin{cases}1 & ,x\le\ln(S/K)\\ 0 & ,x>\ln(S/K)\end{cases} \tag{B5}$$

Instead of solving Eq. (B3) subject to the discontinuous boundary condition described by Eq. (B5), solving for the corresponding characteristic function $\Phi_j(x,\nu,\tau;\omega)$ of the cumulative probability $P_j(x,\nu,\tau)$ is more straightforward. The characteristic function satisfies the same PIDE as $P_j(x,\nu,\tau)$ in Eq. (B3) with the boundary condition

$$\Phi_j(x,\nu,\tau=0;\omega)=e^{i\omega x} \tag{B6}$$

By direct substitution of the solution

$$\Phi_j(x,\nu,\tau;\omega)=\exp\left[C_j(\omega,\tau)+D_j(\omega,\tau)\nu+J_j(\omega,\tau)+i\omega x\right] \tag{B7}$$

Eq. (B3) is reduced to a system of ordinary differential equations:

$$\begin{aligned}\frac{\partial C_j(\omega,\tau)}{\partial\tau}&=\kappa\theta D_j(\omega,\tau)+i\mu\omega\\ \frac{\partial D_j(\omega,\tau)}{\partial\tau}&=aD_j^2(\omega,\tau)+b_jD_j(\omega,\tau)+c_j\\ \frac{\partial J_j(\omega,\tau)}{\partial\tau}&=-\lambda m(i\omega+\delta_j)+\lambda\exp\left[\mu(\delta_j+i\omega)+\frac{1}{2}\sigma^2(\delta_j+i\omega)^2\right]\end{aligned} \tag{B8}$$

which can be solved analytically to yield Eq. (4). The probability $P_j(x,\nu,\tau)$ is obtained using the following relationship [see Heston (1993)]:

$$P_j(x,\nu,\tau)=\frac{1}{2}+\frac{1}{\pi}\int_0^\infty d\omega\,\mathrm{Re}\left[\frac{\Phi_j(x,\nu,\tau;\omega)}{i\omega}\right]\qquad\text{for } j=1,2 \tag{B9}$$