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Crash risk of the euro in the sovereign debt crisis of 2009–2010

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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. We also find evidence of information flow from the sovereign credit default swap market to the currency option market during the crisis.

1. Introduction

Crash risk of currencies has long been the subject of interest in international finance. Related studies, including those of Eichengreen 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 to 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 previous studies on currency crashes focused on developing countries, the onset of the European sovereign debt crisis in

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[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).

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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 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.[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.[4] 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 basis points (bps) for the 5-year CDS and closed at 760 bps on April 28, 2010. As concerns spread, the euro also fell sharply by about 19% as of April 2010 since November 2009 (see Fig. 2 below).

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, which protect investor against the currency depreciation, are very sensitive to sovereign credit risk in the euro area. In view of this finding, first we study the information transmission between the sovereign CDS and currency option markets to examine whether currency option prices anticipate information of sovereign credit risk from CDS spreads. Secondly, we investigate whether sovereign credit risk is an important determinant of deep out-of-the-money put options, after controlling for global risk appetite, funding liquidity constraint, and macro-financial condition.

This paper is related to recent literature on interconnectivity among the corporate CDS, stock and stock option markets. Acharya and Johnson (2007) find that there is incremental information flow from the corporate CDS market to the stock market. They find that the corporate CDS market leads the stock market to anticipating adverse credit information of the reference firm and this finding is linked to informed-trading in credit derivatives. Cremers et al. (2008) show that the implied volatility skews of individual stock options explain a large part of time-series and cross-sectional variations in corporate yield spreads. Cao et al. (2010) document that implied volatility of deep out-of-the-money put options, which depicts the negative tail of the risk-neutral probability of stock returns, is closely related to corporate CDS spreads – because the options provide investors with similar protections against downside risk. They conclude that stock options play an important role in the price discovery process for firms' credit risk.

A number of recent studies on currency crashes use information on currency option prices. 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, and calibrate the crash probability to option prices. Jurek (2009) 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. However, these studies do not incorporate sovereign credit risk into their analyses and modelling frameworks of exchange rate movements.

This paper is structured as follows. Section 2 discusses the data and descriptive statistics. Section 3 examines the information transmission between the sovereign CDS market for euro-area countries and the dollar-euro currency option market. Section 4 studies the contemporaneous interaction between the sovereign CDS and currency option markets based on an econometric analysis. Section 5 contains the conclusion.

2. Data description

We obtain daily OTC European-style dollar-euro option prices at six fixed maturities of 1, 2, 3, 6, 9, and 12 months across five different strike prices from January 2, 2006 to April 30, 2010.[6] The option prices with different strike prices are quoted using the Black–Scholes implied volatilities in terms of at-the-money straddle, 10- and 25-delta risk reversals, and 10- and 25-delta butterfly spreads. As option dealers only use the Black–Scholes formulas to convert quoted volatilities to option prices, the assumptions of constant parameters in the Black–Scholes model are not inconsistent with the use of different implied volatilities at different strikes in our analysis (see Carr and Wu, 2007). 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 investors are benefited from a large swing in the exchange rate.[7] 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. We convert the total 30 market quotes of option prices on each trading day into implied volatilities of dollar-euro put options at five different strikes from 10-delta to 90-delta. The Appendix A presents the details of the conversion.

We collect the 5-year sovereign CDS spreads of 11 countries in the euro area, namely, Austria, Belgium, Finland, France, Germany,

[3] 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.

[4] While 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. 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.

[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.

[6] The option data are from JPMorgan Chase. According to the BIS, the notional amounts outstanding of currency options on the US dollar and euro were US$7540 billion and US$3289 billion respectively at the end of 2009. The daily average turnover of currency options was about US$207 billion in April 2010, and the dollar-euro pair contributed about 28% of the global foreign exchange market turnover. See BIS, *Triennial Central Bank Survey of Foreign Exchange and Derivatives Market Activity in April 2010*, and *BIS Quarterly Review*, September 2010.

[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.

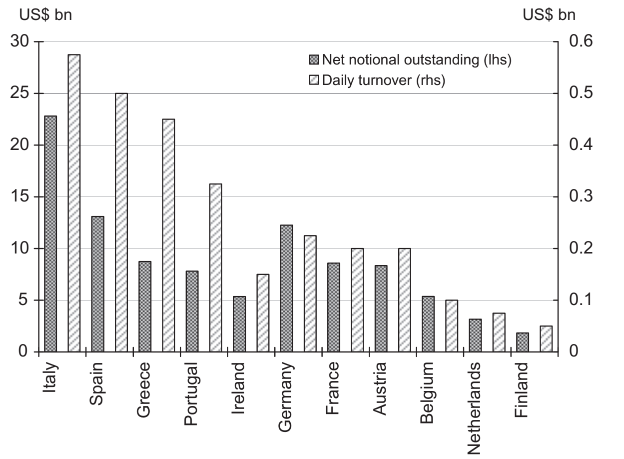

Fig. 1. Net notional amounts outstanding and daily turnover of sovereign CDS contracts. *Note*: Net notional amounts outstanding are the aggregate net protection bought (or equivalently sold) across counterparty. The net notional outstanding shown is as at the end of October 2009 and the average amounts of daily turnover are the average during the period from June 2009 to March 2010. The data are from Depository Trust and Clearing Corporation. See www.dtcc.com.

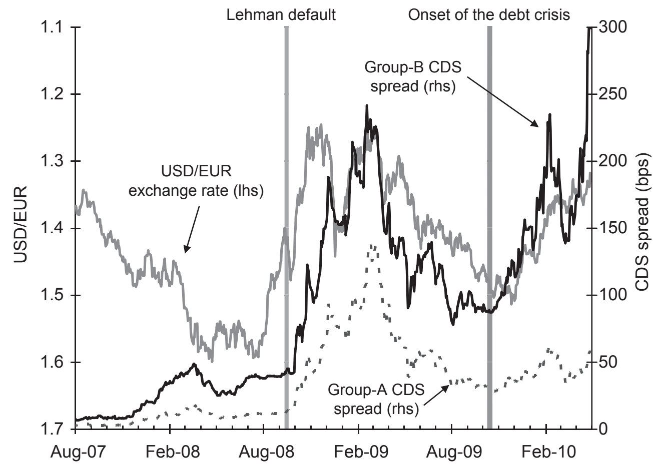

Fig. 2. Sovereign CDS spreads and dollar-euro exchange rate. *Note*: The group-A CDS spread is the average of CDS spreads of Belgium, Austria, Finland, France, Germany and the Netherlands. The group-B CDS spread is the average of CDS spreads of Greece, Portugal, Spain, Ireland and Italy. The default of Lehman Brothers and onset of the sovereign debt crisis are marked at September 15, 2008 and October 14, 2009 respectively.

Greece, Ireland, Italy, the Netherlands, Portugal, and Spain, with active market quotes from Bloomberg covering the period of January 2, 2006 to April 30, 2010.[8] Fig. 1 reports the net notional amounts outstanding (i.e., net protection bought) and average daily amounts of transactions of these CDS contracts during the euro debt crisis. At the end of October 2009, the net notional amounts outstanding of sovereign CDS contracts of these 11 euro-area countries shared around 56% of the total amounts outstanding of the top 40 most actively traded sovereign names. These countries also account for around 40% of the daily sovereign CDS transactions during the period from June 2009 to March 2010, with the transaction concentrate at the 5-year maturity bucket.[9] 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. We present the movements of the simple average CDS spreads of these two groups of countries in Fig. 2.

The upper panel in Table 1 presents the descriptive statistics for the quoted 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 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 January 2, 2006 to August 31, 2009 (middle panel, before the crisis began), and the second period is from September 1, 2009 (1 month before the new government came to power after elections in Greece in October 2009) to April 30, 2010 (lower panel, the crisis period).

In the sample period before the debt crisis, the mean CDS spreads for groups A and B are 20 bps and 42 bps, respectively. The spreads surge sharply to levels of 40 bps and 144 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 risk reversals at 10-delta and 25-delta are 0.17% and 0.10%, respectively, before the debt crisis period but turn to 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 April 29, 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 changes slightly from 10.23% to 11.56%, whereas the average quotes of the corresponding butterfly spreads increase marginally from 1.11% and 0.33% to 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.[10] 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 9.6% to 23.0%. 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. Relatively speaking, OTM implied volatilities are more correlated with the CDS spreads of the group-B countries, while ITM implied volatilities are more correlated with those of the group-A countries.

3. Information flow between sovereign CDS market and currency option market

Given the strong relationship between the option-implied volatility and sovereign CDS spreads, we study their lead-lag relationship by gauging any information flow between the sovereign CDS market and currency option market. We follow the methodology in Acharya and Johnson (2007) to consider the two markets pos-

[8] There is no active sovereign CDS on Cyprus, Luxembourg, Malta, Slovakia, and Slovenia. The CDS data of the sovereign CDS on Ireland has been available since October 12, 2007.

[9] Details of the structure of the sovereign CDS market are in Pan and Singleton (2008).

[10] In this way, the measurement of correlation is not affected by the short-term lead-lag relationship between the two variables.

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 2, 2006 to April 30, 2010							
Mean	10.43	−0.32	−0.19	1.15	0.34	23.26	57.81
Median	9.37	0.00	0.00	1.02	0.29	10.43	26.90
Maximum	25.16	1.73	1.02	3.35	1.00	137.46	366.34
Minimum	5.03	−4.68	−2.75	0.41	0.12	2.02	4.61
Std. dev.	4.14	1.08	0.64	0.73	0.22	28.37	64.75
Skewness	1.22	−1.01	−1.02	1.37	1.38	1.59	1.18
Kurtosis	4.17	3.35	3.36	4.36	4.35	5.36	3.66
No. of obs.	1129						
(b) From January 2, 2006 to August 31, 2009							
Mean	10.23	−0.05	−0.03	1.11	0.33	20.21	42.11
Median	8.84	0.17	0.10	0.94	0.28	3.69	9.34
Maximum	25.16	1.73	1.02	3.35	1.00	137.46	230.99
Minimum	5.03	−4.68	−2.75	0.41	0.12	2.02	4.61
Std. dev.	4.46	0.82	0.48	0.78	0.23	29.64	53.66
Skewness	1.29	−1.26	−1.26	1.42	1.47	1.90	1.62
Kurtosis	3.87	5.86	5.88	4.13	4.20	5.98	4.74
No. of obs.	955						
(c) From September 1, 2009 to April 30, 2010							
Mean	11.56	−1.80	−1.07	1.33	0.41	40.03	143.92
Median	11.58	−2.23	−1.35	1.25	0.38	38.94	140.79
Maximum	13.39	0.68	0.40	1.75	0.53	60.66	366.34
Minimum	10.21	−3.57	−2.10	1.04	0.33	28.47	85.96
Std. dev.	0.64	1.13	0.67	0.24	0.07	8.17	51.37
Skewness	0.09	0.97	0.98	0.55	0.62	0.58	1.21
Kurtosis	2.61	2.55	2.52	1.86	1.93	2.48	5.29
No. of obs.	174						

Note: We report the full sample and sub-samples summary statistics on the quoted 3-month implied volatilities of dollar-euro options and the average CDS spreads of the two groups of euro-area countries. The implied volatilities are quoted as at-the-money implied volatility, 10-delta and 25-delta risk reversals, 10-delta and 25-delta butterfly spreads. 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 statistics are based on daily sampled data. The implied volatilities in terms of percentage points and the CDS spreads are in basis points.

sessing two different but inter-dependent information sets.[11] The price innovations in the two markets are the market-specific information arrivals in additional to the market-wide information set.[12] If the sovereign CDS market acquires forward-looking information and affects the crash risk of the euro, the price innovations of euro-area sovereign CDS spreads should have explanatory power on the future changes in OTM dollar-euro put option-implied volatility. We filter the market-specific price innovations in sovereign CDS spreads by the regression:

$$\Delta CDS_{i,t} = a + b\Delta VOL_t + \sum_{k=1}^{n} c_k \Delta CDS_{i,t-k} + \varepsilon_{CDS_i,t} \quad (1)$$

where ΔVOL_t is the change in the 10-delta dollar-euro option-implied volatility, $\Delta CDS_{i,t}$ are the changes in average CDS spreads of the group-A and -B countries, for $i = 1, 2$. The lagged changes in CDS spread capture the lagged information transmission within the sovereign CDS market. In the regression, the market-specific innovation $\varepsilon_{CDS_i,t}$ can be identified as an independent information arrival that is not anticipated by the currency option market at time t. We model the information flow from the sovereign CDS market to the currency option market using the lagged influences of $\varepsilon_{CDS_i,t}$ on the implied volatility in the following regression:

$$\Delta VOL_t = \alpha + \sum_{k=1}^{n} \beta_k \varepsilon_{CDS_i,t-k} + \sum_{k=1}^{n} \gamma_k \Delta VOL_{t-k} + \varepsilon_{VOL,t}, \quad (2)$$

as reflected by the loading coefficients β_k, $k = 1, 2, \ldots, n$. Acharya and Johnson (2007) use the statistical significance of the point estimate $I = \sum_{k=1}^{n} \beta_k$ to assess the intensity of an information flow. If the information flow is large and permanent, I should be significantly positive.[13]

Similarly, we analyse the reverse information flow from the currency option market to the sovereign CDS market by the regressions:

$$\Delta VOL_t = \tilde{a} + \sum_{k=1}^{n} \tilde{b}_k \Delta CDS_{i,t-k} + \sum_{k=1}^{n} \tilde{c}_k \Delta VOL_{t-k} + \tilde{\varepsilon}_{VOL,t}, \quad (3)$$

$$\Delta CDS_{i,t} = \tilde{\alpha} + \sum_{k=1}^{n} \tilde{\beta}_k \tilde{\varepsilon}_{VOL_i,t-k} + \sum_{k=1}^{n} \tilde{\gamma}_k \Delta CDS_{i,t-k} + \tilde{\varepsilon}_{CDSit}, \quad (4)$$

where the estimate $\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$ measures the intensity of reverse information flow. When there is a robust one-way information flow from the CDS market to the currency option market, I should be significantly positive and $\tilde{I}$ should be statistically insignificant.

We estimate Eqs. (1)–(4) using daily data for the full sample period and the sub-period during the euro debt crisis from September 2009 to April 2010. Table 3 shows that there is substantial information flow from the sovereign CDS market to the currency option market with significant positive estimates of I during the

[11] 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.

[12] Formally, we consider a probability space $(\Omega, \Im, Q)$, where Q is the risk-neutral measure in an arbitrage-free economy, $\Im_t$ is the filtration generated by the underlying state variables (the overall financial market) in such a way that $\Im_t = G_t \vee H_t$, where G_t and H_t are the information sets of the sovereign CDS market and currency option market respectively.

[13] We employ the Wald test for coefficient restriction with the null hypothesis $\sum_{k=1}^{n} \beta_k = 0$. The number of lags is chosen to be $n = 3$ based on the autocorrelation structures of the CDS spreads and implied volatility.

Table 2
Correlation between option-implied volatilities and CDS spreads.

	10-Delta OTM (%)	25-Delta OTM (%)	ATM (%)	75-Delta ITM (%)	90-Delta ITM (%)
Group-A counties					
1-month	16.9	15.3	12.9	11.1	10.4
2-month	19.7	18.1	15.3	13.2	12.3
3-month	20.7	18.3	15.0	12.3	11.1
6-month	24.1	21.4	17.4	14.0	12.5
9-month	25.0	22.1	17.9	14.2	12.6
12-month	25.0	22.0	17.6	13.8	12.2
Group-B countries					
1-month	20.0	18.1	14.4	10.6	8.6
2-month	22.8	20.8	16.5	12.1	9.7
3-month	23.0	20.6	16.3	12.1	9.6
6-month	25.6	22.9	17.9	12.8	9.8
9-month	27.0	24.4	19.2	13.9	10.7
12-month	27.1	24.7	19.7	14.3	11.1

Note: The in-sample correlation between the option-implied volatilities and the two groups of CDS spreads based on weekly changes (every Wednesday). Market quotes of option prices are converted into equivalent quotes in terms of dollar-euro put options (see Appendix A). A dollar-euro put option is a European option of selling euro at the contractual option strike price in an exchange of US dollars at the option maturity. The following abbreviations is used – OTM: out-of-the-money dollar-euro put, ATM: at-the-money dollar-euro put, ITM: in-the-money dollar-euro put. The sample period is from January 2, 2006 to April 30, 2010.

Table 3
Information flow between sovereign CDS and currency option markets.

	Estimate	Std. errors	*t*-Statistics	*p*-Value
(A) Sample period: from January 2, 2006 to April 30, 2010				
Group-A countries				
$I = \sum_{k=1}^{n} \beta_k$	−0.00204	0.018	−0.111	0.912
$\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$	0.527	0.399	1.32	0.187
Group-B countries				
$I = \sum_{k=1}^{n} \beta_k$	0.00404	0.00392	1.03	0.303
$\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$	0.212	1.48	0.143	0.886
(B) Sample period: from September 1, 2009 to April 30, 2010				
Group-A countries				
$I = \sum_{k=1}^{n} \beta_k$	0.0746***	0.024	3.10	0.002
$\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$	−0.449	0.650	−0.069	0.945
Group-B countries				
$I = \sum_{k=1}^{n} \beta_k$	0.00959**	0.0046	2.096	0.038
$\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$	−1.409	2.90	−0.486	0.628

Note: This table summarises the estimation results of Eqs. (1)–(4) for analysing the information flow between the sovereign CDS and currency option markets using the methodology in Acharya and Johnson (2007). $\tilde{I} = \sum_{k=1}^{n} \tilde{\beta}_k$ measures the reverse information flow. The standard errors and *t*-statistics are computed based on the Wald test for coefficient restriction with the null hypotheses $\sum_{k=1}^{n} \beta_k = 0$ and $\sum_{k=1}^{n} \tilde{\beta}_k = 0$. Panel A reports the estimates for the full sample period (January 2, 2006 to April 30, 2010) and panel B reports those for the sub-sample period (September 1, 2009 to April 30, 2010) during the euro debt crisis.
* Significance at 10% level respectively.
** Significance at 5% level respectively.
*** Significance at 1% level respectively.

euro debt crisis. However, in the full sample estimation, the information flow between the two markets is minimal and the direction of flow is mixed.[14] This means that the information flow, which is transient in nature and conditional to the adverse development of sovereign creditworthiness, is primarily from the sovereign CDS market to the currency option market.

The above finding shows a similarity between the information transmission between prices of credit instruments and options in the foreign exchange and equity markets. Cremers et al. (2008) indicate that implied volatilities of individual stock options contain important information for credit spreads of the underlying stocks. Similarly, our finding reflects that currency option prices contain information transmitted from the sovereign CDS spreads during the crisis period. Cao et al. (2010) also find that options market information is highly relevant when explaining the pricing of corporate CDS. However, they identify a robust predictability of future corporate CDS spread changes from current implied volatility innovations of equity options, i.e., information flow from the option prices to CDS spreads. The direction of information flow between the (sovereign/corporate) CDS markets and (currency/stock) option markets is thus different in the foreign exchange and equity markets. As the information flow from the sovereign CDS market to the currency option market is concentrated during the crisis period, our finding is consistent with the existence of hedging by market participants (e.g., European banks) with large exposures to euro-area government papers. These market participants might initially use sovereign CDS to hedge the downside risks of their bond portfolios. When the crisis intensified, they might buy dollar-euro put options to reduce potential losses due to the crash risk of the euro.

In summary, the structure of information transmission reflects that the currency option market responds to adverse information revealed in the sovereign CDS market (i.e., the surge in sovereign CDS spreads), and thus incorporates the impact of a sovereign default in the euro area into the crash risk premium of dollar-euro options.

[14] We obtain a similar conclusion using the pairwise Granger causality test.

Table 4
Determinants of changes in 3-month implied volatilities across different strikes from January 2, 2006 to April 30, 2010.

	10-Delta	25-Delta	ATM	75-Delta	90-Delta
Constant	0.010	0.006	0.002	0.000	−0.001
	(0.15)	(0.04)	(0.04)	(0.01)	(−0.02)
CDS spread (group-A, in bps)	0.028*	0.023*	0.019	0.016	0.015
	(1.85)	(1.67)	(1.39)	(1.17)	(1.06)
CDS spread (group-B, in bps)	0.012***	0.010***	0.008***	0.006**	0.006**
	(4.41)	(3.93)	(3.13)	(2.39)	(1.98)
R-squared	3.58%	2.84%	1.89%	1.22%	0.95%
Adj. *R*-squared	3.08%	2.34%	1.38%	0.71%	0.43%
F-statistic	7.16	5.63	3.70	2.37	1.84
Prob(*F*-statistic)	0.000	0.000	0.000	0.005	0.037
Wald test (Null Hypothesis: $\beta_1 = \beta_2$)					
t-Statistics	1.19	1.07	0.93	0.82	0.80
p-Value	0.2353	0.2836	0.3550	0.4099	0.4248
Total no. of obs.	2324				
No. of countries	11				

Note: This table reports the following pooled panel regression of the 3-month implied volatilities (10-delta, 25-delta, ATM, 75-delta and 90-delta) on the group-A and group-B countries' CDS spreads using weekly changes for the full sample period: $\Delta IVOL_t = \alpha + \beta_1 \Delta CDS_{i,t} \times D_i^A + \beta_2 \Delta CDS_{i,t} \times D_i^B + \nu_{i,t}$, for $i = 1, 2, \ldots, 11$. 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 two groups of countries. The *t*-statistics (in parentheses) are computed from the White cross-sectional standard error. The Wald test of coefficient restriction with the null hypothesis $\beta_1 = \beta_2$ indicates whether the estimated coefficients of the two groups of CDS spreads are statistically different.
* Significance at 10% level respectively.
** Significance at 5% level respectively.
*** Significance at 1% level respectively.

4. Cross-sectional interaction between CDS spreads and currency option prices

The previous section shows the presence of interconnectivity and lead-lag relationship between the sovereign CDS market and currency option market. To understand better the economic sources of such linkage, we focus on the cross-sectional interaction and use panel regression analysis to study how the market expectation of a crash of the euro anticipated in the currency option market is attributed to 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.

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 percentile of the return distributions to capture the jump risk in equity prices.[15] To study the determinants of the euro crash risk, we use the 3-month 10-delta out-of-the-money implied volatility as an indicator of the crash risk. 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.

4.1. Two groups of member countries with sound and weak fiscal positions

We first perform a pooled regression of the 3-month 10-delta implied volatility with the sovereign CDS spreads of the 11 euro-area countries as follows[16]:

$$\Delta IVOL_t = \alpha + \beta_1 \Delta CDS_{i,t} \times D_i^A + \beta_2 \Delta CDS_{i,t} \times D_i^B + \nu_{i,t}. \tag{5}$$

The explanatory variables are a panel set of the 11 countries' sovereign CDS spreads, that is, $CDS_{i,t}$, for $i = 1, 2, \ldots, 11$. We specify the error terms as $\nu_{i,t} = \eta_i + \varepsilon_{i,t}$ to incorporate country fixed effects and adopt the White cross-section robust standard errors to account for the contemporaneous correlation between errors. As the variables are non-stationary, we use weekly differences in the regression to avoid spurious inferences.[17] 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 4 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 = 4.41) than that of the group-A CDS spreads (*t*-statistic = 1.85), where 3.58% 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 bps increases in the group-A and group-B country CDS spreads correspond to increases of 2.8% and 1.2% points, respectively, in the 10-delta implied volatility. The Wald test of coefficient restriction

[15] 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.

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

[17] Section 3 finds that changes in CDS spreads cause changes in option implied volatility. Hence, there is no ambiguity in interpreting the causality relationship in the reduced-form regression.

Table 5
Determinants of changes in 3-month implied volatilities across different strikes from September 1, 2009 to April 30, 2010.

	10-Delta	25-Delta	ATM	75-Delta	90-Delta
Constant	0.001	−0.011	−0.034	−0.060	−0.081
	(0.01)	(−0.35)	(−0.35)	(−0.63)	(−0.81)
CDS spread (group-A, in bps)	0.096***	0.086***	0.075***	0.067***	0.064***
	(3.87)	(4.12)	(4.48)	(4.76)	(4.82)
CDS spread (group-B, in bps)	0.011***	0.009***	0.008***	0.007***	0.007***
	(9.03)	(9.37)	(8.89)	(7.84)	(7.28)
R-squared	22.46%	22.95%	21.78%	19.04%	16.67%
Adj. *R*-squared	19.95%	20.47%	19.26%	16.43%	13.98%
F-statistic	8.98	9.24	8.63	7.29	6.20
Prob(*F*-statistic)	0.000	0.000	0.000	0.000	0.000
Wald test (Null Hypothesis: $\beta_1 = \beta_2$)					
t-Statistics	3.51***	3.72***	4.02***	4.26***	4.32***
p-Value	0.0005	0.0002	0.0001	0.0000	0.0000
Total no. of obs.	385				
No. of countries	11				

Note: This table reports the following pooled panel regression of the 3-month implied volatilities (10-delta, 25-delta, ATM, 75-delta and 90-delta) on the group-A and group-B countries' CDS spreads using weekly changes for the sub-sample period during the euro debt crisis: $\Delta IVOL_t = \alpha + \beta_1 \Delta CDS_{i,t} \times D_i^A + \beta_2 \Delta CDS_{i,t} \times D_i^B + \upsilon_{i,t}$, for $i = 1, 2, \ldots, 11$. 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 two groups of countries. The *t*-statistics (in parentheses) are computed from the White cross-sectional standard errors. The Wald test of coefficient restriction with the null hypothesis $\beta_1 = \beta_2$ indicates whether the estimated coefficients of the two groups of CDS spreads are statistically different.
* Significance at 10% level respectively.
** Significance at 5% level respectively.
*** Significance at 1% level respectively.

suggests that the economic impact of the group-A CDS spreads is marginally stronger than that of the group-B CDS spreads in terms of absolute increases in their 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 bps increase in the group-A CDS spreads will increase the implied volatilities by 2.3%, 1.9%, 1.6% and 1.5% 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 1.3% 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 bps increase in the spreads steepens the volatility skew by about 0.6% points. The results in Table 4 show that the sovereign CDS spreads are statistically related to 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 5 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 0.096 (*t*-statistics = 3.87) and 0.011 (*t*-statistics = 9.03) respectively, with the adjusted *R*-squared increases markedly to 22.5%. This result indicates that sovereign creditworthiness played a major role in determining the euro crash risk during the sample period. The Wald test suggests that the creditworthiness of the group-A countries with more sound fiscal positions has significantly larger economic impact on the euro crash risk than that of the group-B countries with weaker fiscal positions. This may reflect that the currency option market considering the euro crash risk can be significantly larger when interconnectedness between the 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 appears 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.[18] The sovereign credit risk in the group-B countries may spread to the group-A countries if a sovereign default of a group-B country triggers the defaults of these exposures, 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 both euro-area countries with weaker fiscal positions and those with more sound fiscal positions is 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.

4.2. 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. (2011) 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, we include a set of macro-financial variables as control determinants of the 10-delta implied volatility, including the following factors[19]:

[18] 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.

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

(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^2_{USD}) as the ex-post squared return of the index.

(ii) *Global risk appetite*. We use the CBOE VIX volatility index (*VIX*), the market volatility of the US S&P 500 index, to gauge the global risk appetite in the financial market.[20] 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 the 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 carry-trade positions and repatriate funds to US dollars as safe haven.[21] 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*).[22] 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, we expect the term spread of a country's government bonds to be negatively related to the strength of its currency.

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

$$\begin{aligned}\Delta IVOL_t = {} & \alpha + \beta_1 \Delta CDS_{i,t} \times D_i^A + \beta_2 \Delta CDS_{i,t} \times D_i^B + \beta_3 \Delta r^2_{USD,t} \\ & + \beta_4 \Delta VIX_t + \beta_5 \Delta TED_t + \beta_6 \Delta SPX_t + \beta_7 \Delta USTerm_t \\ & + \beta_8 \Delta STOXX_t + \beta_9 \Delta EUTerm_t + \nu_{i,t}. \qquad (6)\end{aligned}$$

We use different specifications of Eq. (6) to isolate the potential effects of multicollinearity. Table 6 shows that 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 8.1% 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 4.3% 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 16.1%, suggesting the importance of controlling the US dollar factor. The impact of the TED spreads (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 1.85 and 4.41 using Eq. (5) to 1.30 and 2.76 using Eq. (6), respectively. The significance of the group-B CDS spreads is robust under the alternative specifications and remains significant at the 1% confidence level. The result supports the hypothesis that 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 we include the stock market returns and the term spreads. This shows that group-A CDS spreads share common characteristics with other macro-financial factors in explaining the euro crash risk in the full sample period.

Focusing on the sub-sample period of the sovereign debt crisis, we expect the effects of the sovereign risk to be more prominent.[23] Table 7 reports that the estimated coefficients of the group-A and -B CDS spreads remain significant under different model specifications, indicating that sovereign risk is a primary driver of the crash risk during the debt crisis. The reduction in *t*-statistics (from 9.03 to 2.93) of the group-B CDS spreads reflects that their movements are partially driven by other macro-financial factors and investors' risk aversion. Regarding the control variables, the macro-financial factors and global risk appetite exhibit higher economic and statistical significance, in which the stock market returns, term spreads, and VIX index altogether explain additional 33.0% 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 is not related to the actual fluctuation in the dollar value. The effects of the sovereign risk persist 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 occur, lead to a large drop in asset prices and aggregate consumption.[24] In the context of asset pricing, our estimation results support the notion 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; Farhi 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 is subsumed by that of the group-A CDS spreads with higher statistical and economic significance. This means 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

[20] 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.

[21] 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.

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

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

[24] We use the term "peso problem" as defined by Cochrane (2005): "A generic term for the effects of small probabilities of large events on empirical work."

Table 6
Determinants of changes in 3-month 10-delta implied volatility of dollar-euro options from January 2, 2006 to April 30, 2010.

	(IV)	(III)	(II)	(I)
Constant	−0.010 (−0.19)	0.009 (0.15)	0.009 (0.16)	0.010 (0.15)
CDS spread (group-A, in bps)	0.019 (1.30)	0.023 (1.49)	0.027* (1.68)	0.028* (1.85)
CDS spread (group-B, in bps)	0.0075*** (2.76)	0.0102*** (3.42)	0.0119*** (4.30)	0.0120*** (4.41)
Dollar squared return (%^{2})	0.056*** (3.00)	0.065*** (3.44)	0.065*** (3.69)	
VIX index (%)	0.076 (1.57)	0.062 (1.47)		
US TED spread (bps)	−0.003 (−0.73)	−0.001 (−0.21)		
Macro-financial variables				
US term spread (bps)	0.0004 (0.04)			
US stock market return (%)	0.170** (2.24)			
EU term spread (bps)	0.012 (1.00)			
EU stock market return (%)	−0.153*** (−3.53)			
R-squared	32.2%	24.0%	19.7%	3.6%
Adj. *R*-squared	31.6%	23.5%	19.2%	3.1%
Log likelihood	−2854.1	−2985.4	−3049.1	−3270.7
F-statistic	57.22	48.37	43.38	7.16
Wald test (Null Hypothesis: $\beta_1 = \beta_2$)				
t-Statistics	0.92	0.98	1.06	1.19
p-Value	0.3554	0.3289	0.2907	0.2353
Total no. of obs.	2313			
No. of countries	11			

Note: This table reports the following extended pooled panel regression of the 3-month 10-delta implied volatility on the group-A and group-B countries' CDS spreads using weekly changes for the full sample period: $\Delta IVOL_t = \alpha + \beta_1 \Delta CDS_{i,t} \times D_i^A + \beta_2 \Delta CDS_{i,t} \times D_i^B + \beta_3 \Delta r^2_{USD,t} + \beta_4 \Delta VIX_t + \beta_5 \Delta TED_t + \beta_6 \Delta SPX_t + \beta_7 \Delta USTerm_t + \beta_8 \Delta STOXX_t + \beta_9 \Delta EUTerm_t + \upsilon_{i,t}$ for $i = 1, 2, \ldots, 11$. 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 two groups of countries. The set of additional explanatory variables includes: (i) US dollar volatility ($\Delta r^2_{USD,t}$), (ii) VIX index (ΔVIX_t), (iii) US-dollar TED spread (ΔTED_t), (iv) weekly returns of S&P 500 index and Dow Jones EURO STOXX 600 index (ΔSPX_t and $\Delta STOXX_t$), and (v) term spreads between 10-year and 2-year yields of the US Treasuries and euro-area government bonds ($\Delta USTerm_t$ and $\Delta EUTerm_t$). The *t*-statistics (in parentheses) are computed from the White cross-sectional standard errors. The Wald test of coefficient restriction with the null hypothesis $\beta_1 = \beta_2$ indicates whether the estimated coefficients of the two groups of CDS spreads are statistically different.
* Significance at 10% level respectively.
** Significance at 5% level respectively.
*** Significance at 1% level respectively.

are important determinants of the euro crash risk during the crisis period.

In summary, empirical results show that sovereign credit risk is an important determinant of the euro crash risk, distinct from other macro-financial factors. Furthermore, the crash risk is not only exposed to the credit creditworthiness of countries with weaker fiscal positions but also to those with more sound fiscal positions.

5. 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 2, 2006 to April 30, 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. We find evidence of information flow from the sovereign CDS market to the currency option market during the crisis. Further econometric 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.

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Appendix A

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

Table 7
Determinants of changes in 3-month 10-delta implied volatility of dollar-euro options from September 1, 2009 to April 30, 2010.

	(IV)	(III)	(II)	(I)
Constant	−0.037	0.038	0.000	0.001
	(−0.38)	(0.36)	(0.00)	(0.01)
CDS spread (group-A, in bps)	0.057***	0.068***	0.089***	0.096***
	(3.74)	(4.52)	(3.57)	(3.87)
CDS spread (group-B, in bps)	0.0054***	0.0071***	0.010***	0.011***
	(2.93)	(6.10)	(8.17)	(9.03)
Dollar squared return ($\%^2$)	0.054	0.087**	0.087*	
	(1.20)	(2.02)	(1.88)	
VIX index (%)	0.228**	0.172***		
	(2.37)	(4.71)		
US TED spread (bps)	−0.034	0.002		
	(−0.64)	(0.05)		
Macro-financial variables				
US term spread (bps)	0.0337*			
	(1.81)			
US stock market return (%)	0.193*			
	(1.80)			
EU term spread (bps)	−0.027			
	(−1.64)			
EU stock market return (%)	−0.122			
	(−0.98)			
R-squared	55.3%	47.4%	26.9%	22.5%
Adj. *R*-squared	53.0%	45.3%	24.4%	20.0%
Log likelihood	−340.1	−371.6	−434.9	−446.3
F-statistic	23.81	22.16	10.51	8.98
Wald test (Null Hypothesis: $\beta_1 = \beta_2$)				
t-Statistics	3.63***	4.14***	3.25***	3.51***
p-Value	0.0000	0.0000	0.0013	0.0005
Total no. of obs.	385			
No. of countries	11			

Note: This table reports the extended pooled panel regression of the 3-month 10-delta implied volatility on the group-A and group-B countries' CDS spreads using weekly changes for the sub-sample period during the euro debt crisis: $\Delta IVOL_t = \alpha + \beta_1 \Delta CDS_{i,t} \times D_i^A + \beta_2 \Delta CDS_{i,t} \times D_i^B + \beta_3 \Delta r^2_{USD,t} + \beta_4 \Delta VIX_t + \beta_5 \Delta TED_t + \beta_6 \Delta SPX_t + \beta_7 \Delta USTerm_t + \beta_8 \Delta STOXX_t + \beta_9 \Delta EUTerm_t + \upsilon_{i,t}$ for $i = 1, 2, \ldots, 11$. 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 two groups of countries. The set of additional explanatory variables includes: (i) US dollar volatility ($\Delta r^2_{USD,t}$), (ii) VIX index (ΔVIX_t), (iii) US-dollar TED spread (ΔTED_t), (iv) weekly returns of S&P 500 index and Dow Jones EURO STOXX 600 index (ΔSPX_t and $\Delta STOXX_t$), and (v) term spreads between 10-year and 2-year yields of the US Treasuries and euro-area government bonds ($\Delta USTerm_t$ and $\Delta EUTerm_t$). The *t*-statistics (in parentheses) are computed from the White cross-sectional standard errors. The Wald test of coefficient restriction with the null hypothesis $\beta_1 = \beta_2$ indicates whether the estimated coefficients of the two groups of CDS spreads are statistically different.
* Significance at 10% level respectively.
** Significance at 5% level respectively.
*** Significance at 1% level respectively.

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

where S is the dollar-euro exchange rate, K is the strike price, σ_{imp} is the implied volatility, r and q are the US dollar and euro interest rates, τ is the time-to-maturity and $N(\cdot)$ is the cumulative normal distribution. The definitions of the market quotes of currency options are as follows:

- A delta-neutral straddle is 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.
- A risk reversal quote is 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

$$rr10 = IV(\Delta_{call} = 10) - IV(\Delta_{put} = 10)$$
$$rr25 = IV(\Delta_{call} = 25) - IV(\Delta_{put} = 25), \tag{A2}$$

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

$$bf10 = [IV(\Delta_{call} = 10) + IV(\Delta_{put} = 10)]/2 - IV(str)$$
$$bf25 = [IV(\Delta_{call} = 25) + IV(\Delta_{put} = 25)]/2 - IV(str), \tag{A3}$$

where $IV(str)$ is the delta-neutral straddle implied volatility. We recover the implied volatilities at different strikes (deltas) by solving Eqs. (A2) and (A3), and obtain the exchange rate and interest rate (LIBOR) data from Bloomberg.

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