Cross Section of Option Returns and Volatility-of-Volatility*

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Abstract

This paper presents a robust new finding that there is a significantly negative relation between the equity option returns and the forward-looking volatility-of-volatility (VOV). After controlling for numerous existing option and stock characteristics, the VOV effect remains significantly negative. It also survives many robustness checks. A conceptual model provided in this paper reveals the pricing mechanism behind the VOV effect, i.e., the negative relation is due to the negative market price of the VOV risk. As investors dislike the VOV risk, they are willing to pay a high premium to hold options on high VOV stocks. The high-low return spread on option portfolios sorted on VOV cannot be explained by standard risk factors, and survives the double sorting on a variety of control variables. This confirms that the VOV effect is economically and statistically significant.

Keywords: Volatility-of-volatility; option returns; cross section.

JEL Classifications: G12, G13.

1. Introduction

Baltussen, Van Bekkum, and Van Der Grient (2017) have found that the forward-looking volatility of volatility (VOV) is a stock characteristic and can negatively and significantly predict the cross section of stock returns. In terms of the cross section of option returns, a variety of volatility-based characteristics are documented that they are important determinants (e.g., Goyal and Saretto (2009); Cao and Han (2013); Vasquez (2017) and Hu and Jacobs (2017)). VOV, as a volatility-based characteristic, may have some predictive power in the cross section of option returns. Unfortunately, there is litter literature testing this hypothesis. To fill this gap, this paper newly tests whether there is a negative relation between the cross section of equity option returns and the equity's VOV, which captures the risk of uncertainty about volatility. The hypothesis is motivated by a conceptual model adopted from Huang and Shaliastovich (2014) and Christoffersen, Fournier, and Jacobs (2017)), in which the expected equity option returns are negatively predicted by the equity's VOV.

To test the hypothesis, we examine a cross section of equity option returns each month. We firstly filter out options whose stocks have ex-dividend dates prior to option expiration and eliminate options with moneyness that is lower than 0.975 or higher than 1.025. At the end of each month, we then collect a pair of options that are closest to being at-the-money (ATM), have shortest maturity among those with more than one month to expiration and have the same maturity. Finally, we obtain around 88,000 observations for both calls and puts. Following Bakshi and Kapadia (2003) and Cao and Han (2013), we consider the daily rebalanced delta-hedged gains scaled by the initial underlying stock price as the option returns. At the end of each month, we therefore construct one delta-hedged call option portfolio that is long a call option and short a delta number of stocks with the net investment earning the risk-free rate. Each option portfolio is held until maturity and daily rebalanced.

After that, empirically, we find the expected observation, i.e., the higher the VOV, the lower the expected option returns. Fama and MacBeth (1973) cross-sectional regressions from 1996 to 2016 conclude that there is a significant and negative relation between the option future returns and VOV. This is the key new finding in this paper. Our results are robust after controlling for numerous option and stock characteristics. A portfolio that buys the lowest decile ranked by VOV and sells the highest decile earns about 0.16% held until maturity, which is economically and statistically significant and cannot be explained by standard risk factors. The profit survives the double sorting on a variety of control variables.

We further check whether the definitions of option returns and the VOV measures matter to our conclusion as robustness checks and then find that the negative VOV effect holds with the delta-hedged put option returns, delta-hedged gains with different scales, monthly rebalanced delta-hedged option returns, delta-neutral straddle returns, the volatility of 6-month volatility (VOV6M) and the alternative VOV measure.[1]

This paper contributes to the finance literature in a number of ways. First, the paper extends the study of the forward-looking VOV of the individual stocks. Previous literature has focused on the aggregate VOV, which is treated as a market factor. For example, Hollstein and Prokopczuk (2017) measure the aggregate VOV as the VIX Volatility (VVIX) index, which is identified in a model-free manner from the index and VIX option prices, and confirm that the VVIX index is priced in the stock market. It commands an economically substantial and statistically significant negative risk premium. Agarwal, Arisoy, and Naik (2017) measure the aggregate VOV as the monthly returns on a lookback straddle strategy written on the VIX and find that it is priced in the cross section of hedge fund returns. Instead of the cross-section of stock and hedge returns, Huang and Shaliastovich (2014) and Park (2015) show that the aggregate VOV, measured by the VVIX index, is a significant risk factor for both S&P 500 index option returns and VIX option returns. In contrast to Huang and Shaliastovich (2014) and Park (2015), we focus on the relation between the equity option returns and the equity's VOV, which is a stock characteristic rather than a market factor.

To the best of our knowledge, ours is the first investigation to examine whether uncertainty about individual stock's volatility is priced in the cross section of option returns.[2] The

[1] More checks are given in Internet Appendix.

[2] Cao, Han, Tong, and Zhan (2017) compute uncertainty in stock volatility (VOL-of-VOL) as the standard deviation of percentage change in the daily realized volatility over one month, in order to capture the model risk studied by Green and Figlewski (1999). Compared with our VOV, their VOL-of-VOL is not involved in option data so that it is not forward-looking. In line with Cao et al. (2017), we obtain estimates of daily volatility for each stock in each month by applying from the EGARCH (1,1) model to a rolling window of past 12-month daily stock returns and obtain VOL-of-VOL calculated from the standard deviation of percentage change in the daily realized volatility over one month. There is a comparison based on Fama and MacBeth (1973) cross-sectional regressions provided in Table IA.1. It shows that the predictive power of VOV is almost not affected by controlling for VOL-of-VOL.

paper closest in spirit to our investigation is by Baltussen et al. (2017), who find that VOV of individual stocks (as a measure of uncertainty about volatility) is an important stock characteristic in the cross section of stock returns and the negative VOV effect survives any robustness checks and holds in both U.S. and European stock markets. We follow their definition of the individual VOV and extend it to predict the cross section of option returns.[3] Coincidentally, in this paper, the negative VOV effect is found in the equity option market.

Second, our paper contributes to the growing literature on the cross-section of option returns. In particular, for the volatility-based option return predictors,[4] Goyal and Saretto (2009) find a zero-cost trading strategy of options, that is long (short) in the portfolio with a large positive (negative) realized-implied volatility spread, can produce an economically and statistically significant average monthly return. Cao and Han (2013) further document that the daily rebalanced delta-hedged equity option return decreases monotonically with an increase in the idiosyncratic volatility of the underlying stock. Hu and Jacobs (2017) analyze the relation between expected option returns and the volatility of the underlying securities and find that returns on call (put) option portfolios decrease (increase) with underlying stock volatility. In addition, Vasquez (2017) finds that the slope of the implied volatility term structure is positively related to future option returns. Those studies particularly focus on volatility. However, their predictors do not involve the forward-looking VOV. This paper fills this gap and tests whether there is a negative relation between the cross section of option returns and VOV.

[3]The VOV in our paper is like the individual realized volatility of implied volatility, while the VVIX is the aggregate implied volatility of the implied volatility. Even though, Hollstein and Prokopczuk (2017) compare the realized volatility of VIX with the VVIX and find that the prediction power will be decreased or even vanish after controlling for the systematic risk, we have to use the realized volatility of implied volatility as our VOV measure due to the unavailability of individual implied volatility index option data.

[4]For other predictors, Bali and Murray (2013) find a strong negative relation between the risk-neutral skewness of stock returns and the skewness asset returns, comprised of two option positions (one long and one short) and a position in the underlying stock. Boyer and Vorkink (2014) provide a strong negative relationship between the risk-neutral skewness of option returns and the cross section of equity options. Byun and Kim (2016) investigate the relation between the option returns and the underlying stock's lottery-like characteristics. Furthermore, Muravyev (2016) shows that the inventory risk faced by market-makers has a first-order effect on option prices. Kanne, Korn, and Uhrig-Homburg (2016) and Christoffersen, Goyenko, Jacobs, and Karoui (2018) provide evidence of a strong effect of the underlying stock's illiquidity on option prices. Recently, Cao et al. (2017) have comprehensively studied the option return predictability and find that the cross-section of delta-hedged equity option returns can be predicted by a variety of underlying stock characteristics and firm fundamentals, including idiosyncratic volatility, past stock returns, profitability, cash holding, new share issuance, and dispersion of analyst forecasts.

The remainder of our paper is organized as follows. Section 2 presents a conceptual model. Section 3 shows our data and variables. Section 4 studies the cross section of option returns. The robustness checks are given in Section 5 and option trading strategies are provided in Section 6. Section 7 concludes. Appendix A.1 gives the option database screening procedure and Appendix A.2 shows the control variable construction.

2. A Conceptual Model

Before we empirically test the VOV effect in the cross-section of option returns, we firstly answer three questions: (i) What is VOV? (ii) How does VOV predict the equity option returns? (iii) What's kind of option returns we should choose?

In order to do that, we introduce a simple model adopted from Huang and Shaliastovich (2014) and Christoffersen et al. (2017). There are N stocks in the financial market and the risk-free rate is r. For stock i, under the physical measure $\mathbb{P}$, its process follows

$$\begin{aligned} \frac{dS_t^i}{S_t^i} &= \left(\phi_t^i + r\right) dt + \sqrt{v_t^i} dB_{1,t}^i, \\ dv_t^i &= \theta_t^i dt + \sqrt{w_t^i} dB_{2,t}^i, \\ dw_t^i &= \gamma_t^i dt + \sigma_w^i \sqrt{w_t^i} dB_{3,t}^i, \end{aligned} \tag{1}$$

where $B_{m,t}^i$ ($m = 1, 2, 3$, respectively) are Brownian motions in the stock returns, the stock return variance and the variance of variance for each stock i. We assume all Brownian motions can be correlated, i.e., $dB_{m,t}^i dB_{n,t}^j = \rho_{mn}^{ij}$ for $i, j = 1, 2, ..., N$ and $m, n = 1, 2, 3$. In addition, the equity premium of stock i, ϕ_t^i, can be a function of v_t^i, w_t^i and S_t^i; the drift term in the variance θ_t^i can be a function of v_t^i; and the drift term in the variance of variance γ_t^i can be a function of w_t^i.

Equation (1) basically shows that VOV (i.e., w_t^i) is assumed as a stock characteristic embedded in the dynamics of the stock returns. Baltussen et al. (2017) has documented that VOV is a stock characteristic and is priced in the cross-section of stock returns. In this paper, we further investigate whether VOV, as a stock characteristic, is priced in the cross-section of option returns. In oder to link VOV and the option returns, we transform Equation (1) under the risk-neutral measure $\mathbb{Q}$,

$$\begin{aligned}
\frac{dS_t^i}{S_t^i} &= rdt + \sqrt{v_t^i}d\widetilde{B}_{1,t}^i, \\
dv_t^i &= \left(\theta_t^i - \lambda_{v,t}^i\right) dt + \sqrt{w_t^i}d\widetilde{B}_{2,t}^i, \\
dw_t^i &= \left(\gamma_t^i - \lambda_{w,t}^i\right) dt + \sigma_w^i\sqrt{w_t^i}d\widetilde{B}_{3,t}^i,
\end{aligned} \tag{2}$$

with an assumption, i.e., $\lambda_{v,t}^i = \lambda_v^i v_t^i$ and $\lambda_{w,t}^i = \lambda_w^i w_t^i$ are the volatility and VOV risk premiums, where λ_v^i and λ_w^i capture the market prices of the volatility risk and the VOV risk of stock i, respectively. If we assume that investors dislike the volatility and VOV risks, then their market prices will be negative, so that $\lambda_v^i < 0$ and $\lambda_w^i < 0$. The Brownian motions under the risk-neutral measure $\mathbb{Q}$ become,

$$\widetilde{B}_{1,t}^i = B_{1,t}^i + \frac{\phi_t^i}{\sqrt{v_t^i}}, \quad \widetilde{B}_{2,t}^i = B_{2,t}^i + \frac{\lambda_{v,t}^i}{\sqrt{w_t^i}}, \quad \widetilde{B}_{3,t}^i = B_{3,t}^i + \frac{\lambda_{w,t}^i}{\sqrt{w_t^i}}. \tag{3}$$

The dynamics of the stochastic discount factor (SDF) can be given by

$$\frac{d\pi_t}{\pi_t} = -rdt - \sum_{i=1}^{N}\left(\frac{\phi_t^i}{\sqrt{v_t^i}}dB_{1,t}^i + \frac{\lambda_{v,t}^i}{\sqrt{w_t^i}}dB_{2,t}^i + \frac{\lambda_{w,t}^i}{\sqrt{w_t^i}}dB_{3,t}^i\right). \tag{4}$$

The SDF captures all risks existing in the financial market. As Brownian motions can be correlated, $3\times N$ Brownian motions can be reduced to a less number of uncorrelated Brownian motions. Our SDF is a special case of Christoffersen et al. (2017) when the idiosyncratic variance risk is eliminated in the individual equity price.

At time t, an option price of the stock i with strike K and maturity date T can be denoted as $C_t^i := C(S^i, v^i, w^i, t; K, T)$.[5] Applying Itô's lemma to C_t^i yields,

$$dC_t^i = \frac{\partial C^i}{\partial S^i}dS_t^i + \frac{\partial C^i}{\partial v^i}dv_t^i + \frac{\partial C^i}{\partial w^i}dw_t^i + D_t^i dt, \tag{5}$$

where D_t^i is the drift component and can be obtained from the martingale constrain of $e^{-rt}C_t^i$

[5] Actually, C_t^i can be any derivatives or portfolios related to S^i, v_t^i and w_t^i.

under the risk-neutral measure $\mathbb{Q}$, i.e.,

$$\frac{\partial C^i}{\partial S^i} S_t^i r + \frac{\partial C^i}{\partial v^i}\left(\theta_t^i - \lambda_{v,t}^i\right) + \frac{\partial C^i}{\partial w^i}\left(\gamma_t^i - \lambda_{w,t}^i\right) + D_t^i - rC_t^i = 0. \tag{6}$$

After solving the the drift component D_t^i from Equation (6),

$$D_t^i = r\left(C_t^i - \frac{\partial C^i}{\partial S^i} S_t^i\right) - \frac{\partial C^i}{\partial v^i}\left(\theta_t^i - \lambda_{v,t}^i\right) - \frac{\partial C^i}{\partial w^i}\left(\gamma_t^i - \lambda_{w,t}^i\right), \tag{7}$$

we get the future option price $C_{t+\tau}^i$ from Equation (5), i.e.,

$$\begin{aligned} C_{t+\tau}^i =& C_t^i + \int_t^{t+\tau} \frac{\partial C^i}{\partial S^i} dS_u^i + \int_t^{t+\tau} \frac{\partial C^i}{\partial v^i} dv_u^i + \int_t^{t+\tau} \frac{\partial C^i}{\partial w^i} dw_u^i \\ &+ \int_t^{t+\tau} r\left(C_t^i - \frac{\partial C^i}{\partial S^i} S_u^i\right) du - \int_t^{t+\tau} \frac{\partial C^i}{\partial v^i}\left(\theta_u^i - \lambda_{v,u}^i\right) du - \int_t^{t+\tau} \frac{\partial C^i}{\partial w^i}\left(\gamma_u^i - \lambda_{w,u}^i\right) du. \end{aligned} \tag{8}$$

Following Bakshi and Kapadia (2003), the delta-hedged option gain can be defined as

$$\Pi_{t,t+\tau}^i \equiv C_{t+\tau}^i - C_t^i - \int_t^{t+\tau} \frac{\partial C^i}{\partial S^i} dS_u^i - \int_t^{t+\tau} r\left(C_u^i - \frac{\partial C^i}{\partial S^i} S_u^i\right) du. \tag{9}$$

Plugging (8) and (1) into (9), we get

$$\Pi_{t,t+\tau}^i = \int_t^{t+\tau} \frac{\partial C^i}{\partial v^i} \lambda_{v,u}^i du + \int_t^{t+\tau} \frac{\partial C^i}{\partial w^i} \lambda_{w,u}^i du + \int_t^{t+\tau} \frac{\partial C^i}{\partial v^i} \sqrt{w_u^i} dB_{2,u}^i + \int_t^{t+\tau} \frac{\partial C^i}{\partial w^i} \sigma_w \sqrt{w_u^i} dB_{3,u}^i. \tag{10}$$

The expected delta-hedged gain therefore can be solved as[6]

$$E_t[\Pi_{t,t+\tau}^i] = E_t\left(\int_t^{t+\tau} \frac{\partial C^i}{\partial v^i} \lambda_{v,u}^i du\right) + E_t\left(\int_t^{t+\tau} \frac{\partial C^i}{\partial w^i} \lambda_{w,u}^i du\right). \tag{11}$$

Using the assumption, $\lambda_{v,t}^i = \lambda_v^i v_t^i$ and $\lambda_{w,t}^i = \lambda_w^i w_t^i$, according to Bakshi and Kapadia (2003)

[6] The expect gain of holding an option is simply given by

$$E_t\left[C_{t+\tau}^i - C_t^i - \int_t^{t+\tau} rC_u^i du\right] = E_t\left(\int_t^{t+\tau} \frac{\partial C^i}{\partial S^i} \phi_u^i du\right) + E_t\left(\int_t^{t+\tau} \frac{\partial C^i}{\partial v^i} \lambda_{v,u}^i du\right) + E_t\left(\int_t^{t+\tau} \frac{\partial C^i}{\partial w^i} \lambda_{w,u}^i du\right).$$

Without being delta-hedged, the expect gain of holding an option is also contributed by the equity premium from the underlying stocks. In order to eliminate the impact from the equity premium, we consider the delta-hedged gain throughout this paper.

and Huang and Shaliastovich (2014), Equation (11) can be expressed by

$$\frac{E_t[\Pi^i_{t,t+\tau}]}{S^i_t} = \lambda^i_v \beta^i_{v,t} v^i_t + \lambda^i_w \beta^i_{w,t} w^i_t, \tag{12}$$

where $\beta^i_{v,t} > 0$ and $\beta^i_{w,t} > 0$ are the sensitivities to the volatility and VOV risks, respectively.[7] The denominator S^i_t is due that C^i_t, $\frac{\partial C^i}{\partial v^i}$ and $\frac{\partial C^i}{\partial w^i}$ are homogeneous of degree 1 in S^i_t.

Equation (12) gives the relation between the expected delta-hedged gain, scaled by the stock price, and the volatility and VOV risks. It reveals several important intuitions. (i) the VOV effect is driven by the market price of the VOV risk. If investors dislike the VOV risks, the VOV effect will be negative, i.e., the higher the VOV, the lower the expected option returns. Equation (12) indeed provides an intuitive risk-based explanation for the VOV effect. (ii) As the volatility effect is simultaneously modelled by Equation (12), it also provides an alternative risk-based explanation for the results in Cao and Han (2013), i.e., the volatility effect is negative. Furthermore, the realized-implied volatility spread (RV-IV) is a proxy of the variance risk premium $\lambda^i_{v,t} = \lambda^i_v v^i_t = \frac{1}{dt}\left(E[dv^i_t] - E^{\mathbb{Q}}[dv^i_t]\right)$. Equation (12) therefore additionally explains the positive RV-IV effect, documented by Goyal and Saretto (2009). (iii) The expected delta-hedged gain scaled by the initial stock price eliminates the stock movements, so that it is a function of only the volatility and VOV risks. Taking this advantage, the literature of the cross-section of the option returns mainly focuses on the delta-hedged option returns, e.g., Goyal and Saretto (2009); Cao and Han (2013) and Cao et al. (2017). (iv) As C^i_t can be a portfolio, any delta-hedged or delta-neutral option portfolios should satisfy Equation (12), for example, the delta-neutral straddles studied by Goyal and Saretto (2009); Cremers, Halling, and Weinbaum (2015) and Vasquez (2017).

Based on the above conceptual model, we know that VOV is a stock characteristic, similar to the volatility of stock returns. VOV can negatively predict the future option returns (i.e., delta-hedged gains scaled by the underlying stock prices), if investors dislike the VOV risk. In the following sections, we shall test the hypothesis that whether there is a negative relation between the cross section of option returns and VOV.

[7] The sign of $\beta^i_{v,t}$ ($\beta^i_{w,t}$) is determined by $\frac{\partial C^i}{\partial v} > 0$ ($\frac{\partial C^i}{\partial w^i} > 0$).

3. Data and Variables

3.1 Option data

Option data are obtained from the Ivy DB database provided by OptionMetrics, from 04 January 1996 to 29 April 2016. The data include daily closing bid and ask prices, trading volume, option interest, implied volatility, delta and vega. Closing option prices are calculated as the midpoint of the closing bid and ask prices. The monthly stock prices are obtained from CRSP. Following Goyal and Saretto (2009); Cao and Han (2013); Boyer and Vorkink (2014) and Byun and Kim (2016), firstly, we keep option data at the end of each month and merge them with the CRSP data, keeping the sample if the closing price for the underlying stock from CRSP is below 97% or above 103% of the closing price of the underlying stock from the OptionMetrics database. Then we filter the option data based on Appendix A.1. After that, we filter out options whose stocks have ex-dividend dates prior to option expiration and eliminate options with moneyness (S/K) lower than 0.975 or higher than 1.025.[8] At the end of each month, we collect a pair of options that are closest to being at-the-money (ATM) and have the shortest maturity among those with more than one month to expiration. Following Cao and Han (2013), the maturity of the options we then pick each month has the same maturity. We therefore drop the options whose maturity is different from that of the maturity. Finally, we have 88,336 observations for both calls and puts. Our sample totally considers 5,069 stocks and around 396 stocks per month.

Panel A, Table 1 shows that the average moneyness of the chosen option is almost one, with a standard deviation of only 0.01. The average delta of call options is close to 0.5 and the average delta of put options is close to -0.5. In line with Cao and Han (2013), the time to maturity of the chosen options ranges from 47 to 52 calendar days across different months, with an average of 50 days. On average, the open interest and the trading volume of calls are greater than puts. These short-term options are the most actively traded. Following Cao and Han (2013), we calculate the bid-ask spread as the ratio of the difference between ask

[8]In line with Cao and Han (2013) and Cao et al. (2017), we alternatively keep options with moneyness (S/K) between 0.8 and 1.2. Using this filter, we obtain 224,504 observations for both calls and puts. The average call option return is -0.29% with the median of -0.37% and the standard deviation of 3.18%. The results are given in Table IA.8–IA.10 in Internet Appendix and the VOV effect is even much stronger in this scenario.

and bid quotes of options over the midpoint of bid and ask quotes at the end of each month, and measure demand by the option open interest at the end of each month scaled by monthly stock trading volume, i.e., (option open interest/stock volume)$\times 10^3$. The average bid-ask spreads of call and put options are same, around 0.14. Because of greater open interest, the demand of call options is higher than the demand of put options.

[Insert Table 1]

3.2 Option Returns

The delta-hedged gain defined in Equation (9) is from the continuous trading. In the reality, the hedge should be rebalanced discretely. Consider a portfolio of an option (e.g., call option) that is hedged discretely N times over a period $[t, t+\tau]$ where the hedge is rebalanced at each of the dates t_i, $i = 0, 1, ..., N-1$ (where we define $t_0 = t$ and $t_N = t+\tau$). In line with Bakshi and Kapadia (2003) and Cao and Han (2013), we define the daily rebalanced delta-hedged gain as follows.

$$\Pi^i_{t,t+\tau} = C^i_{t+\tau} - C^i_t - \sum_{i=0}^{N-1} \Delta^i_{C,t_n} \left(S^i_{t_{n+1}} - S^i_{t_n} \right) - \sum_{i=0}^{N-1} r_{t_n} \tau_{t_n} \left(C^i_{t_n} - \Delta^i_{C,t_n} S^i_{t_n} \right), \qquad (13)$$

where Δ^i_{C,t_n} is the delta of the option C^i at date t_n; r_{t_n} is the annualized risk-free rate at date t_n and τ_{t_n} is the number of calendar days between t_n and t_{n+1} scaled by 365. The daily risk-free rate is obtained from the Kenneth R. French Data Library.

Obviously, the initial investment in the delta-hedged option portfolio is zero, i.e., $\Pi^i_{t,t} = 0$, so that $\Pi^i_{t,t+\tau}$ is the dollar return of the option portfolio. As $\Pi^i_{t,t+\tau}$ is homogeneous of degree 1 in S^i_t, we scale the dollar return $\Pi^i_{t,t+\tau}$ by the stock price S^i_t. Therefore, consistent with Equation (12), the return of the option on stock i can be defined as

$$r^i_{t,t+\tau} = \frac{\Pi^i_{t,t+\tau}}{S^i_t}. \qquad (14)$$

At the end of each month, we construct one option portfolio and hold it until maturity (which is on average 50 calendar days).[9] Then the option return is the daily rebalanced

[9]We also run the cross-sectional regressions of option returns held until the end of month. The average

delta-hedged gain scaled by the initial stock price.[10] We repeat this procedure each month during the sample period and then we get a time series of option returns for each equity. In the main content, we force on the call option returns defined in Equation (14) and provide the results of the alternative returns in the robustness checks. From Panel B in Table 1, we find that the average call option return is −0.26% with the standard deviation of 2.91%. The median is higher than the mean, that is −0.49%.

3.3 VOV measure

Following Baltussen et al. (2017), we define the implied volatility (IV) as the average of the ATM call and put implied volatilities, using the volatility surface standardized options with a delta of 0.50 and maturity of 30 days. These data are obtained from Ivy DB OptionMetrics. For each month t, the unscaled VOV is defined as the standard deviation of the ATM 30-day IV, that is

$$VOV_t^{un,i} = sd(IV_d^i), \tag{15}$$

where IV_d^i is the daily IV on day d of month t for stock i.

For a random variable iv (i.e., IV), we have $sd(A \times iv) = A \times sd(iv)$ where A is a constant. This indicates that the volatility of IV tends to be larger for the IV with larger magnitude. In order to filter the volatility level effect from VOV, in line with Baltussen et al. (2017), we scale $VOV_t^{un,i}$ by the mean of IV, i.e.,[11]

$$VOV_t^i = \frac{sd(IV_d^i)}{mean(IV_d^i)}. \tag{16}$$

We require that there be at least 13 no-missing observations to calculate VOV. As IV is the implied volatility, VOV is forward-looking. According to Baltussen et al. (2017), VOV captures the uncertainty in investors' assessment of the risks that surround future stock prices. Epstein and Ji (2014) formulate a model to explain how investors' ambiguity on volatility

call option return is −0.15% with the median of −0.37% and the standard deviation of 2.19%. The results are given in Tables IA.11–IA.13 in Internet Appendix and they are qualitatively same.

[10] In OptionMetrics, delta is missing in somedays. Therefore, we only rebalance the portfolio if delta is not missing on that day, otherwise we hold it until the day has a non-missing delta.

[11] Using the unscaled VOV does not change our conclusion. See Table IA.2 in Internet Appendix. Expectedly, for monthly Fama and MacBeth (1973) cross-sectional regressions, the magnitude and the significance of the average VOV coefficient decrease a little after controlling IVOL or IV.

affects the asset prices. VOV does capture ambiguous volatility. Huang and Shaliastovich (2014); Park (2015); Hollstein and Prokopczuk (2017) and our conceptual model show that investors, who care uncertainty about volatility, are willing to pay a positive premium. The negative market price of the VOV risk leads to the negative VOV effect.

Column (2), Panel C, Table 1 shows that for each year, the median of VOV across different stocks is around $5 - 8\%$. Across different years, the medians of VOV are slightly different. For example, in 2008, VOV reaches the maximal median of 8.35 during the sample period we use. The unscaled VOV, reported in Column 1, Panel C, Table 1, varies a similar pattern of VOV.

3.4 Control variables

The daily and monthly stock returns, stock prices, trading volume and share outstanding are obtained from CRSP, and accounting and balance sheet data are obtained from COMPUSTAT, for calculating other control variables: the market beta (BETA), the log market capitalization (SIZE), the book-to-market ratio (BM), the return in the past month (REV), the cumulative return from month $t-12$ to month $t-2$ (MOM), the log illiquidity (LN_ILLIQ), the maximum daily return (MAX) over the current month t, the idiosyncratic volatility (IVOL), the realized skewness (RS) and the realized kurtosis (RK) based on daily returns over the most recent 12 months.

By using volatility surface data provided by Ivy DB OptionMetrics, we are able to calculate the model-free implied volatility (IV), the implied skewness (IS), the implied kurtosis (IK), the volatility term structures (VTS) and the implied volatility innovations (dCIV and dPIV). Finally, following Goyal and Saretto (2009), we calculate the realized-implied volatility spread (RV_IV) by using daily stock returns obtained from CRSP and the implied volatility obtained from Ivy DB OptionMetrics. The details of control variable construction are provided in Appendix A.2. Following Cao and Han (2013) and Cao et al. (2017), we winsorize all independent variables each month at the 0.5% level in order to eliminate the outliers. The risk factors, including Fama and French (1993) three factors (MKT, SMB, HML), Carhart (1997) momentum factor (UMD) and Fama and French (2015) five factors (RMW, CMA), are obtained from the Kenneth R. French Data Library.

Panel D, Table 1 gives the summary statistics, which are close to the existing literature, e.g., Cao and Han (2013); Byun and Kim (2016); Cao and Han (2013) and Baltussen et al. (2017). Their correlations are given in Panel E, Table 1. The unscaled VOV, as a volatility-related variable, is correlated to IVOL and IV, with a same correlation of 0.55. As VOV is scaled by the average IV, VOV is almost independent of IV, with a correlation of 0.02. The correlation between VOV and IVOL also reduces to 0.14. In addition, we find that there is a high correlation between SIZE and LN_ILLIQ, at a value of -0.91. It is intuitive, as the small size stocks normally have high illiquidity.

4. Empirical results

In this section, we test the hypothesis of whether there is a negative relation between the cross section of option returns and VOV, based on the monthly Fama and MacBeth (1973) cross-sectional regressions,[12] after controlling for existing popular determinants. The dependent variable is the future option return, defined in (14), and the independent variables are predetermined at the end of month t.

4.1 Univariate regression

As a benchmark, we present the univariate regression on VOV in the first column of Table 2, which shows that the delta-hedged call option returns are negatively related to the VOV, without any control variables. The average coefficient of VOV is -0.018, with a significant Newey and West (1987) t-statistic of -4.20. This confirms that VOV can negatively predict the future option returns. This negative prediction further documents that the market price of the VOV risk is negative and investors indeed dislike the VOV risk. Our empirical result is therefore consistent with the intuition behind the conceptual model given in Section 2.

[Insert Table 2]

[12] Fama and MacBeth (1973) cross-sectional regressions are widely used to test the relation between the cross section of returns and the individual security variables, e.g., Brennan, Chordia, and Subrahmanyam (1998); Bali, Cakici, and Whitelaw (2011); Cao and Han (2013); Vasquez (2017) and others.

4.2 Controlling for firm-specific characteristics

All options are written on the underlying stocks. Straightforwardly, the underlying stock characteristics may affect the relation between the option returns and VOV. Cao et al. (2017) find that the delta-hedged equity option returns can be predicted by a variety of firm-specific characteristics. Panel A, Table 2 reports the regression results after controlling for firm-specific characteristics, i.e., the market beta (BETA), the log market capitalization (SIZE), the book-to-market ratio (BM), the return in the past month (REV) and the cumulative return from month $t-12$ to month $t-2$ (MOM).

The average coefficient of VOV remains negative and highly significant in all regressions in Panel A, Table 2. All firm-specific characteristics does not materially affect the magnitude and statistical significance of the VOV coefficient. The average VOV coefficient varies from -0.018 to -0.020 and the Newey and West (1987) t-statistic ranges from -3.98 to -4.75. This shows that the VOV effect cannot be explained by the firm-specific characteristics. The result is expected, due to that VOV is almost independent of all firm-specific characteristics, based on the correlations given in Panel E, Table 1.

4.3 Controlling for return distribution characteristics

According to Cao and Han (2013), the idiosyncratic volatility (IVOL) as a proxy of arbitrage costs, is significantly and negatively related to the option returns. The higher premium investors have to pay is due to the arbitrage costs. Model 2 in Panel B, Table 2 shows that the IVOL coefficient is negative but not significant. Comparing Model 1 and Model 2 in Panel B, we find the VOV coefficient slightly decreases. The inconsistency between our result and Cao and Han's (2013) finding may be form the different data filters. Tables IA.8 in Internet Appendix gives further checks with an alternative data filter and shows that the average coefficient of IVOL will be significant if we use the same data filter of moneyness in Cao and Han (2013), i.e., keeping options with moneyness between 0.8 and 1.2. Using a thinner moneyness range may generate deeper ATM options, so that the arbitrage costs become lower due to the higher liquidity. Across different data filters, the VOV effect remains negative and significant.

Byun and Kim (2016) suggest that call options written on the lottery-like stocks underperform. We control for the lottery demand factor, MAX, and find the VOV coefficient is not affected. Furthermore, the average MAX coefficient is insignificant with a t-statistic of 0.069. We could not find Byun and Kim's (2016) observation in daily rebalanced delta-hedged call option returns.

Based on the existing option pricing models (e.g., Pan (2002) and Carr and Wu (2004)), the jumps are the key factors for the option prices. We therefore control for the realized skewness (RS) and the realized kurtosis (RK). Based on Model 4 and Model 5, we indeed find a negative and significant relation between the option returns and jumps. The average coefficient of RS in Model 4 is -0.00055 with a Newey and West (1987) t-statistic of -3.96 and the average coefficient of RK in Model 5 is -0.00013 with a Newey and West (1987) t-statistic of -5.32. RS and RK seem to have some predictive power for the option returns. Among these return distribution characteristics, RK decreases the magnitude and the significance of the VOV coefficient most. The average VOV coefficient reduces to -0.015 with a t-statistic of -3.21 after controlling for RK. This indicates that VOV may have some jump information. Even that, the negative VOV effect remains significant.

4.4 Controlling for limits to arbitrage

Cao and Han (2013) provide some evidence that the highly negative delta-hedge premium is related to limits to arbitrage. Cao and Han (2013) consider three variables as proxies of limits to arbitrage, i.e., the option demand (DEMAND), the option bid-ask spread (BID_ASK) which is a proxy of the option illiquidity and the log stock illiquidity (LN_ILLIQ). Proxies of limits to arbitrage essentially capture the option demand pressure and the illiquidity. From Model 6 in Panel B, Table 2, we observe that the higher the option demand (DEMAND), the lower the expected option returns. This is in line with the demand-based option pricing theory in Garleanu, Pedersen, and Poteshman (2009). Furthermore, Model 4 in Panel B, Table 2 shows that the higher the stock illiquidity (LN_ILLIQ), the lower the expected option returns. This is consistent with Kanne et al. (2016) and Christoffersen et al. (2018) who provide evidence of a strong effect of the underlying stock's illiquidity on option prices. After controlling for all limits-to-arbitrage variables, the average VOV coefficient even increases.

Therefore, the VOV effect does come from limits to arbitrage.

4.5 Controlling for option-based characteristics

Hu and Jacobs (2017) find a negative relation between expected call option returns and the volatility of stock returns. In this paper, we use the implied volatility (IV) as a proxy of the volatility. Bali and Murray (2013) further suggest that the implied skewness (IS) can predict the future returns of skewness assets.[13] Goyal and Saretto (2009) find that the realized-implied volatility spread (RV_IV) can produce an economically and statistically significant average monthly option return. Recently, Vasquez (2017) has found that the slope of the implied volatility term structure (VTS) is positively related to future option returns. In order to separate the VOV effect from these existing predictors, we control these predictors in the regressions.

Furthermore, An, Ang, Bali, Cakici, et al. (2014) find that the implied volatility innovations (dCIV and dPIV) can predict the future stock returns. The increase or decrease of the forward-looking implied volatility, which represents the investors' expectation of the market moving direction in the future, may have some predictive power for the future option returns. Due to that, we are also interested in investigating the effects of the implied volatility innovations on the future option returns. All results are given in Panel D, Table 2.

First, Model 2 shows the average IV coefficient is -0.010 with a t-statistic of -5.28. The option returns are negatively related to the IV. This is consistent with Hu and Jacobs (2017) and is also identical to our conceptual model. From Models 3, we indeed find the strong predictive power from IS, which is in line with Bali and Murray (2013). The positive and significant RV_IV coefficient in Model 5 suggests that the higher the realized-implied volatility spread (RV_IV), the higher the option returns. This is the same as the finding in Bakshi and Kapadia (2003); Goyal and Saretto (2009); Cao and Han (2013) and Cao et al. (2017). The positive RV_IV effect is very intuitive. Bakshi and Kapadia (2003) suggest that

[13] We also use the IS calculated by using Bakshi, Kapadia, and Madan (2003) method and give the results in Table IA.3 in Internet Appendix. Roughly speaking, two measures work similarly. As Bakshi et al. (2003) method is restricted to the availability of the data to calculate the implied moments, more than 60% of stocks have missing IS. This is why the average VOV coefficient in Column 1, Table IA.3 is less significant than that in Column 1, Table 2. In this paper, we therefore consider the construction approach in Bali, Hu, and Murray (2016), so that we can get enough observations.

the returns of delta-hedged option portfolios can be a proxy of the variance risk premium and the RV_IV self is a proxy of the variance risk premium. Therefore, RV_IV can positively predict the future option returns. Our conceptual model also confirms this observation. The most influential control variable is VTS. The average VTS coefficient is 0.032 with a significant Newey and West (1987) t-statistic of 7.85, based on Model 6. Vasquez (2017) finds a significant and positive relation between the VTS and the straddle returns. Our results suggest that there is also a significant and positive relation between the VTS and the delta-hedged option returns. Model 7 shows that the implied volatility innovation from calls (dCIV) has a significant and negative coefficient, at a value of -0.022 with a t-statistic of -4.36. This effect in the cross section of option returns is opposite to that in the cross section of stock returns, documented in An et al. (2014). A positive increase in the implied volatility leads to the more negative expected option returns. In other words, investors dislike the increase in the implied volatility and they are willing to pay a premium to hold options whose implied volatility tends to increase. Finally, based on all regressions in Panel D, we find the strength of the negative relation between the option returns and VOV is not reduced, after controlling for these option-based characteristics.

5. Robustness checks

In this section, we provide several robustness checks for our new finding along different option returns and different VOV proxies.

5.1 Different option returns

5.1.1 Delta-hedged put option returns

The results in the previous section are based on the delta-hedged call option returns. We additionally calculate delta-hedged put option returns and give the summary statistics in Row 2, Panel B, Table 1. The average put option return is -0.04% with the standard deviation of 2.94%, which is much higher than the average call option return, while their medians are very close (i.e., -0.49% for calls and -0.28% for puts) and their correlation (unreported) is over 0.94.

Table 3 reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged put option returns. The result are almost the same with call option return's results in Table 2. This indicates that the VOV effect remains for the delta-hedged put option returns. There are two observations that are different with the call option return's: (i) The IVOL effect is stronger in Panel B, Table 3, compared with the call option returns in Table 2. This is intuitive. The put options are less liquid than the call option implied by Panel A, Table 1. The arbitrage costs (i.e., IVOL) of put options are more expensive. (ii) The average IS coefficient becomes significantly positive. The higher the IS, the higher the expect put option returns. Intuitively, for holding put options, investors do like the downside jumps in the future, which will lead to a low underlying stock price. Therefore, put options on stocks with big forward-looking downside jumps (i.e., high IS put options) are expected to achieve high option returns.

[Insert Table 3]

5.1.2 Alternative scales

Goyal and Saretto (2009) directly use the delta-hedged gains as option returns. As a robustness test, we also consider these dollar returns. The statistics of dollar returns $\Pi_{t,\tau}$ are given in Row 1, Panel B, Table 1. The average dollar return is -7.32%. In other words, the average loss of holding an delta-hedged option portfolio until maturity is \$0.0732. We provide the firm-level cross-sectional regression results of delta-hedged gains in Table 4, which is consistent with the results of delta-hedged gains scaled by the initial stock price.

[Insert Table 4]

We further scale the delta-hedged gain by the call option price (C_t^i) following Bakshi and Kapadia (2003), $\Pi^i_{t,t+\tau}/C^i_t$, and the absolute value of the securities involved ($\Delta^i_t S^i_t - C^i_t$) following Cao and Han (2013) and Cao et al. (2017), $\Pi^i_{t,t+\tau}/(\Delta^i_t S^i_t - C^i_t)$. Row 1, Panel B, Table 1 gives their summary statistics. For both types of option returns, the cross-sectional regression results in Tables 5 and 6 are qualitatively same with the results in Table 2.

[Insert Table 5]

[Insert Table 6]

5.1.3 Monthly rebalanced option returns

Option and stock trading involves significant costs, and strategies that hold over a certain period $[t, t+\tau]$ incur these costs only at initiation. In line with Goyal and Saretto (2009) and Cao et al. (2017), we consider the monthly rebalanced delta-hedged gains, which can be defined as

$$\Pi_{t,t+\tau}^{M,i} = C_{t+\tau} - \Delta_t^C S_{t+\tau} - \left(C_t - \Delta_t^C S_t\right)\left(1 + r_t\tau\right), \tag{17}$$

to calculate the option returns. Equation (17) is a special case of Equation (13) when $N = 1$, i.e., the option portfolio is only hedged at initiation. From Row 3, Panel B, Table 1, we find that the monthly rebalanced option returns $r_{t,t+\tau} = \Pi_{t,\tau}^M / S_t$ are close to the daily rebalanced option returns in statistics. The average monthly rebalanced return is -0.18%, which is slightly larger than the average daily rebalanced return, -0.26%. Their correlation (unreported) is 0.62. Expectedly, the regression results given in Table 7 are qualitatively same with the results given in Table 2.

[Insert Table 7]

5.1.4 Delta-neutral straddle returns

The relation between the expected delta-hedged gain and VOV in Equation (12) is applicable for any delta-neutral option portfolios. Due to that, following Goyal and Saretto (2009), we finally consider the dollar gains of delta-neutral straddles,

$$\Pi_{t,t+\tau}^{S,i} = c_{t+\tau}^i + p_{t+\tau}^i - \left(c_t^i + p_t^i\right)\left(1 + r_t\tau\right), \tag{18}$$

where c_t^i and p_t^i are ATM call and put options at date t, respectively and have same strike price. As two options used to construct each straddle (i.e., simultaneously long a call and a put) are ATM and the delta of ATM call is around 0.5 and the delta of ATM put is around -0.5 according to Panel A, Table 1, these straddles are delta-neutral.[14] Each portfolio is constructed at initiation and held until maturity.

[14]If options are not ATM, a delta-neutral straddle can be constructed by long a call and long $-\Delta_{c,t}^i / \Delta_{p,t}^i$ number of put, where $\Delta_{c,t}^i$ ($\Delta_{p,t}^i$) is the delta of the call (put) option at time t.

Row 4, Panel B, Table 1 shows that the average straddle return (i.e., $r_{t,t+\tau} = \Pi^S_{t,\tau}/S_t$) is -0.13% with the standard deviation of 11.99%. The correlation (unreported) between the straddle returns and the daily rebalanced call option returns is 0.58, and the correlation (unreported) between the straddle returns and the monthly rebalanced call option returns is 0.98. This indicates that the delta-neutral straddle returns and delta-hedged option returns consistently capture the risk premiums in a similar pattern. Unsurprisingly, a same conclusion is made in the cross section of straddle returns in Table 8.

[Insert Table 8]

5.2 Different VOV measures

5.2.1 Term structure of VOV

Vasquez (2017) investigates the information embedded in the implied volatility term structure and finds that the slope of the implied volatility term structure is positively related to future option returns. This inspires that the implied volatility term structure causes the VOV term structure. We therefore consider the volatility of volatility (VOV6M), which is defined as the standard deviation of the ATM 6-month IV6M scaled by its mean,

$$VOV6M^i_t = \frac{sd(IV6M^i_d)}{mean(IV6M^i_d)}, \tag{19}$$

where IV6M is the average of the ATM call and put implied volatilities, using the volatility surface standardized options with a delta of 0.50 and maturity of six months.

Column 3, Panel C, Table 1 reports the 10th percentile (p10), 50th percentile (p50) and 90th percentile (p90) of the VOV6M across different years. Overall, the 6-month VOV6M is smaller than the 30-day VOV. This leads to the slope of the term structure of the VOV, VOV6M−VOV, is negative. The average slope (unreported) is around -4%.[15] Even that, the VOV6M still varies in a similar pattern of VOV, across different years. Their correlation (unreported) is 0.81. The Fama and MacBeth (1973) cross-sectional regression results are

[15] We do find some predictive power from the slope of the term structure of VOV, while its prediction depends on whether we control either VOV or VOV6M. As this is not our focus, in this paper, we only study the option return predictability by using VOV6M.

given in Table 9. We find that the significance of the VOV6M coefficient is larger than the significance of the VOV coefficient. It seems that the volatility of longer-maturity volatility has more predictive power. This is consistent with the intuition that the 6-month VOV6M is more informative than the 30-day VOV, in terms of predicting the future option returns (over on average 50 calendar days).

[Insert Table 9]

5.2.2 Alternative VOV proxies

Agarwal et al. (2017) gives an alternative way to define VOV, i.e., the difference between the natural log of the maximum of IV and the natural log of the minimum of IV in month t,

$$VOV_t^{al,i} = \ln\left(\max(IV_d^i)\right) - \ln\left(\min(IV_d^i)\right). \tag{20}$$

The summary statistics of the alternative VOV are given in Column 4, Panel C, Table 1. Roughly speaking, the alternative VOV varies similar to VOV (in Column 2). Actually, the correlation (unreported) between the alternative VOV and the VOV reaches 0.96. The alternative VOV therefore captures almost the same information with VOV. As a result, their predictive power is qualitatively same, documented by the Fama and MacBeth (1973) cross-sectional regressions in Table 10.

[Insert Table 10]

6. Portfolio Formation and Trading Strategy

In this section, we study the relation between option returns and VOV by using the portfolio sorting approach, in order to confirm the previous results based on Fama and MacBeth (1973) cross-sectional regressions.

6.1 Univariate portfolios sorted on VOV

Firstly, at the end of each month, we rank the delta-hedged option portfolios into 5 deciles, based on VOV, and then form the 5 portfolios and calculate the equal-weighted monthly returns of those 5 portfolios, respectively. Table 11 reports the average returns of the 5 portfolios, each of which consists of long positions in daily rebalanced delta-hedged call options, ranked in a given decile by VOV. Table 11 also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low" row.

[Insert Table 11]

Column 1, Table 11 shows that the average subsequent returns of the 5 portfolios range from −0.24 to −0.40. More importantly, we find the first three portfolios have same average return, −0.24. This indicates that the VOV effect is very persistent. The option portfolios with high VOV will be repeated in the future. Following Bali et al. (2011), we run the firm-level cross-sectional regression of VOV on lagged predictors. Table 12 reports the average coefficients, Newey and West (1987) t-statistics and the R-square. The R-square of the univariate regression of lagged VOV is 19.6%, which documents that VOV has the substantial cross-sectional explanatory power. Option portfolios with high VOV tend to exhibit similar features in the following month. Other predictors all have univariate R-square of less than 5%. The average high-low return spread is −0.16% with a Newey and West (1987) t-statistic of −2.90 in Column 1, Table 11. In other words, a portfolio held until maturity that buys the lowest decile ranked by VOV and sells the highest decile can earn 0.16%.[16]

[Insert Table 12]

We use common risk factor models, i.e., the CAPM model, the Fama and French (1993) three-factor model, the Carhart (1997) four-factor model and the Fama and French (2015) five-factor model, to explain the significant negative high-low return spread. The second to last columns in Table 11 give the results and show that the high-low return spread on option portfolios sorted on the VOV cannot be explained by common risk factor models.

6.2 Bivariate portfolios sorted on control variables and the VOV

In line with the studies in Section 4, we consider two-way sorts–one based on the existing predictors and the second based on VOV. We first rank the delta-hedged option portfolios

[16]If we use the delta-hedged option portfolios held until the end of month to form 5 portfolios sorted on VOV, the average high-low return spread is −0.15% with a even more significant t-statistic of −4.32 in Column 1, Table IA.12.

into 5 deciles, based on each control variable, and then sequentially rank each decile into another 5 deciles, based on VOV. Finally, we calculate the equal-weighted returns for each VOV decile across 5 control deciles. Table 13 reports the average returns of the 5 portfolios after controlling for the existing predictors and the average high-row return spread.

[Insert Table 13]

Similar to the univariate sorting result, the VOV effect is still economically and statistically significant after controlling for 18 variables in Table 13. The all average high-low return spreads vary the almost same value with the one-way sort (i.e., -0.16%). This indicates that the VOV effect is not contributed by other existing predictors. Therefore, the portfolio sorting approach confirms the conclusion based on Fama and MacBeth (1973) cross-sectional regressions, i.e., the VOV effect is significant and negative in the option market.[17]

7. Conclusion

This paper provides a comprehensive study of the relation between the delta-hedged option returns and the volatility-of-volatility (VOV). Based on Fama and MacBeth (1973) cross-sectional regressions and the portfolio sorting, we find a negative relation between option returns and VOV, which is economically and statistically significant. This new finding is regarded as the main contribution in this paper and is robust after controlling for numerous risk factors and existing predictors. The negative VOV effect survives any robustness checks.

Our new finding also shows that VOV as a stock characteristic is priced by investors, with a negative market price of the VOV risk. Investors indeed dislike uncertainty about volatility of individual stocks, so that they are willing to pay a high premium to hold options with high VOV. In addition, the VOV effect further suggests that it is important and fruitful to consider the VOV risk in option pricing models, e.g., Huang and Shaliastovich (2014).

[17] The returns based on two-way sorts after controlling for common risk factors are given in Tables IA.4–IA.7 in Internet Appendix and they are similar with the raw returns in Table 13.

A. Appendix

A.1 Option database screening procedure

1. Underlying Asset Is an Index: Optionmetrics “index flag” (index_flag) is nonzero.

2. AM Settlement: The option expires at the market open of the last trading day, rather than the close. Optionmetrics “am settlement flag”(am_set_flag) is nonzero.

3. Nonstandard Settlement: Optionmetrics “special settlement flag” (ss_flag) is nonzero.

4. Abnormal Price: The price is less than \$1/8; the bid price is zero or missing or is higher than the ask price; the price violates arbitrage bounds.

5. Abnormal Implied Volatility: Implied volatility is less than zero or missing;

6. Abnormal Delta: Delta is less than −1 or larger than +1.

7. Zero Open Interest: Open interest is zero or missing.

A.2 Control variable construction

A.2.1 Firm-specific characteristics

- BETA: We run the market model at the daily frequency in month t to obtain the monthly beta of an individual stock,

$$r_{i,d} - r_{f,d} = \alpha_i + \beta_{1,i} MKT_{d-1} + \beta_{2,i} MKT_d + \beta_{3,i} MKT_{d+1} + \varepsilon_{i,d}, \tag{21}$$

  where $r_{i,d}$ is the return on stock i on day d, MKT_d is the market excess return on day d, and $r_{f,d}$ is the risk-free rate on day d. The sum of the estimated slop coefficients, $\hat{\beta}_{1,i} + \hat{\beta}_{2,i} + \hat{\beta}_{3,i}$, is the energy market beta of stock i in month t.

- SIZE: Firm size is measured as the natural log of the market value of equity at the end of the month for each stock.

- Book-to-Market Ratio (BM): We compute the book-to-market ratio in month t of a firm using the market value of its equity at the end of December of the previous year and the book value of common equity plus balance-sheet deferred taxes for the firm's latest fiscal year ending in the prior calendar year, according to Fama and French (1993) and Davis, Fama, and French (2000).

- Short-Term Reversal (REV): Following Jegadeesh (1990) and Lehmann (1990), we define short-term reversal for each stock in month t as the return on the stock over the previous month from $t-1$ to t.
- Momentum (MOM): Following Jegadeesh and Titman (1993), the momentum variable for each stock in month t is defined as the cumulative return from month $t-12$ to month $t-2$.

A.2.2 Limits to arbitrage

- Option Bid-Ask Spread (BID-ASK): Option bid-ask spread is the ratio of the difference between ask and bid quotes of option over the midpoint of bid and ask quotes at the end of each month.
- Option Demand (DEMAND): Option demand is measured by option open interest at the end of each month scaled by monthly stock trading volume, according to Cao and Han (2013), i.e., (option open interest/stock volume)$\times 10^3$.
- Stock Illiquidity (ILLIQ): Following Amihud (2002), the illiquidity, for each stock in month t is defined as the annual average of the ratio of the absolute daily stock return to its dollar trading volume over month t,

$$ILLIQ_{i,t} = 1/D_{i,t} \sum_{d=1}^{D_{i,t}} |R_{i,d}|/VOLD_{i,d} \times 10^6, \tag{22}$$

where $R_{i,d}$ is the return on stock i on day d; D_t is the number of trading days in month t; and $VOLD_{i,t}$ is the monthly trading volume of stock i in dollars.

A.2.3 Return distribution characteristics

- Maximum (MAX): MAX is the maximum daily return within a month, according to Bali et al. (2011).

- Idiosyncratic Volatility (IVOL): Following Ang, Hodrick, Xing, and Zhang (2006), we run the market model at the daily frequency,

$$r_{i,d} - r_{f,d} = \alpha_i + \beta_{i,MKT} MKT_d + \beta_{i,SMB} SMB_d + \beta_{i,HML} HML_d + \varepsilon_{i,d}, \tag{23}$$

  where $r_{i,d}$ is the return on stock i on day d, MKT_d is the market return on day d, and $r_{f,d}$ is the risk-free rate on day d. Idiosyncratic volatility of each stock in month t is defined as the standard deviation of daily residuals in month t, $IVOL_{i,t} = sd(\varepsilon_{i,d})$.

- Realized Skewness (RS): Realized skewness of stock i in month t is defined as the skewness of daily returns over the most recent 12 months.

- Realized Kurtosis (RK): Realized kurtosis of stock i in month t is defined as the kurtosis of daily returns over most recent 12 months.

A.2.4 Option-based characteristics

- Implied Volatility (IV): Implied volatility is the average of the at-the-money (ATM) call and put implied volatilities, using the volatility surface standardized options with a delta of 0.50 and maturity of 30 days, $IV = \frac{CIV_{50}+PIV_{50}}{2}$, on the last trading day of each month.

- Implied Skewness (IS): Following Bali et al. (2016), the implied skewness is the difference between the ATM call and put implied volatilities with a delta of 0.25 and maturity of 30 days, $IS_{t,\tau} = CIV_{25} - PIV_{25}$, on the last trading day of each month.

- Implied Kurtosis (IK): Following Bali et al. (2016), the implied kurtosis is the difference between the sum of the 30-day ATM call and put implied volatilities with a delta of 0.25 and a delta of 0.50, $IK_{t,\tau} = (CIV_{25} + PIV_{25}) - (CIV_{50} + PIV_{50})$, on the last trading day of each month.

- Realized-Implied Volatility Spread (RV_IV): Following Goyal and Saretto (2009), realized-implied volatility spread is the difference between RV and IV, where the annualized realized volatility (RV) of stock i in month t is defined as the square root of 252 times the standard deviation of daily returns over month t, $RV_{i,t} = sd(R_{i,d}) \times \sqrt{252}$.

- Implied Volatility Innovation. According to An et al. (2014), implied volatility innovation of calls $dCIV_{i,t} = CIV_{i,t} - CIV_{i,t-1}$ and implied volatility innovation of puts $dPIV_{i,t} = PIV_{i,t} - PIV_{i,t-1}$, where CIV and PIV are the ATM call and put implied volatilities with a delta of 0.50 and maturity of 30 days, respectively.

- Volatility Term Structures (VTS): Following Vasquez (2017), $VTS = IV6M - IV$, where $IV6M$ is the average of the ATM call and put implied volatilities, using the volatility surface standardized options with a delta of 0.50 and maturity of six months. VTS in this paper captures the slope of the implied volatility term structure between one month and six months.

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Table 1: Summary Statistics

This table reports the descriptive statistics of option returns, volatility-of-volatility (VOV) and control variables used to predict monthly rebalanced delta-hedged option returns. The option sample period is from January 1996 to April 2016. In Panel A, firstly, we keep option data at the end of each month and merge them with the CRSP data and keep the sample if the closing price for the underlying stock from CRSP is below 97% or above 103% of the closing price of the underlying stock from the OptionMetrics database. Then we filter the option data based on Appendix A.1. After that, we filter out options whose stocks have ex-dividend dates prior to option expiration and eliminate options with moneyness (S/K) lower than 0.975 or higher than 1.025. At the end of each month, we collect a pair of options that are closest to being at-the-money (ATM) and have the shortest maturity among those with more than one month to expiration. The stock prices, strikes and option prices are obtained from Ivy DB OptionMetrics. The monthly stock prices are obtained from CRSP. In Panel B, at the end of each month, we construct one delta-hedged call (put) option portfolio, that is long a call (put) option and short delta number of stocks. This option portfolio is held until maturity. Then the option return is the daily rebalanced delta-hedged gain scaled by the initial stock price. We repeat this procedure each month during the sample period and then we get a time series of option returns for each equity. The daily risk-free rate is obtained from the Kenneth R. French Data Library. Days to maturity is the number of calendar days until the option expiration. Moneyness is the ratio of stock price to option strike price. Delta and vega are the option delta and vega according to the Black-Scholes model. The option bid-ask spread is the ratio of the difference between ask and bid quotes of option to the midpoint of the bid and ask quotes at the end of each month. Option demand is measured by option open interest at the end of each month scaled by monthly stock trading volume, i.e., (option open interest/stock volume)$\times 10^3$. In Panel C, the unscaled VOV is defined as the standard deviation of the ATM 30-day IV; VOV is the unscaled VOV scaled the mean of the ATM 30-day IV; VOV6M is the standard deviation of the ATM 180-day IV6M scaled by its mean; and the alternative VOV is defined as the difference between the natural log of the maximum of IV and the natural log of the minimum of IV in month t. Panel D reports the time-series average of the cross-sectional statistics of common predictors: the market beta (BETA), the log market capitalization (SIZE), the book-to-market ratio (BM), the return in the past month (REV), the cumulative return from month $t-12$ to month $t-2$ (MOM), the log illiquidity (LN_ILLIQ), the maximum daily return (MAX) over the current month t, the idiosyncratic volatility (IVOL), the realized skewness (RS) and the realized kurtosis (RK) based on daily returns over the most recent 12 months, the implied skewness (IS), the implied kurtosis (IK), the volatility term structures (VTS), the implied volatility innovations (dCIV and dPIV) and the realized-implied volatility spread (RV_IV). The details of variable construction are provided in Appendix A.2. All of these variables are winsorized each month at the 0.5% level. The daily and monthly stock returns, stock prices, trading volume and share outstanding are obtained from CRSP, and accounting and balance sheet data are obtained from COMPUSTAT. Panel E reports correlations among the VOV and all control variables.

	mean	p50	sd	p10	p25	p75	p90
Calls (88,336)							
Days to maturity	50	50	2	47	50	51	52
SK (%)	99.82	99.76	1.43	97.91	98.58	101.00	101.89
volume	126	6	730	0	0	46	204
open_interest	1372	201	5487	13	50	821	2830
delta	0.53	0.54	0.05	0.46	0.50	0.57	0.59
vega	6.15	4.88	6.64	1.82	2.90	7.67	11.34
Bid-ask spread	0.14	0.11	0.15	0.04	0.06	0.17	0.27
Demand	0.04	0.01	0.09	0.00	0.00	0.03	0.09
Puts (88,336)							
Days to maturity	50	50	2	47	50	51	52
SK (%)	99.85	99.80	1.43	97.92	98.61	101.03	101.90
volume	75	0	467	0	0	20	107
open_interest	849	100	3883	10	24	433	1626
delta	-0.47	-0.46	0.05	-0.54	-0.50	-0.43	-0.41
vega	6.14	4.87	6.64	1.82	2.89	7.66	11.32
Bid-ask spread	0.15	0.11	0.16	0.04	0.06	0.17	0.29
Demand	0.02	0.01	0.08	0.00	0.00	0.02	0.05

Table 1: Summary Statistics (cont'd)

Panel B: Options Returns							
	mean	p50	sd	p10	p25	p75	p90
(1) Daily rebalanced calls (%)							
$r_{t,t+\tau} = \Pi_{t,\tau}/S_t$	-0.26	-0.49	2.91	-2.79	-1.52	0.59	2.31
$\Pi_{t,\tau}$	-7.32	-15.44	128.05	-91.95	-48.66	18.74	75.27
$\Pi_{t,\tau}/C_t$	-4.08	-9.84	43.04	-43.79	-27.72	11.26	38.15
$\Pi_{t,\tau}/(\Delta_t S_t - C_t)$	-0.57	-1.05	6.45	-6.03	-3.25	1.26	4.98
(2) Daily rebalanced puts (%)							
$r_{t,t+\tau} = \Pi_{t,\tau}/S_t$	-0.04	-0.28	2.94	-2.60	-1.31	0.85	2.62
(3) Monthly rebalanced calls(%)							
$r_{t,t+\tau} = \Pi^M_{t,\tau}/S_t$	-0.18	-1.06	5.82	-5.64	-3.42	1.94	6.15
(4) Monthly rebalanced straddles (%)							
$r_{t,t+\tau} = \Pi^S_{t,\tau}/S_t$	-0.13	-1.93	11.99	-11.16	-6.70	4.24	12.64

Table 1: Summary Statistics (cont'd)

Panel C: VOV												
	(1) VOV^{un} (%)			(2) VOV (%)			(3) VOV6M (%)			(4) VOV^{al}(%)		
Year	p10	p50	p90	p10	p50	p90	p10	p50	p90	p10	p50	p90
1996	0.72	1.90	5.87	2.52	5.20	11.04	1.04	2.60	6.68	9.47	18.69	38.64
1997	0.73	1.99	5.79	2.31	5.05	11.17	0.96	2.49	6.84	8.65	18.42	37.23
1998	0.83	2.31	7.29	2.39	5.31	12.45	1.00	2.76	7.55	8.81	19.02	41.88
1999	0.88	2.41	7.52	2.01	4.72	10.98	0.87	2.45	7.13	7.47	16.76	36.39
2000	1.14	3.28	9.95	2.10	5.18	11.76	0.87	2.47	7.18	7.83	17.83	38.68
2001	1.08	2.93	8.44	2.46	5.84	12.86	1.16	2.94	7.57	8.87	19.92	40.02
2002	1.09	2.94	7.80	2.94	6.65	14.14	1.44	3.35	8.07	10.73	22.82	45.31
2003	0.95	2.24	5.38	3.22	6.38	11.88	1.45	3.00	6.47	11.89	22.21	39.09
2004	0.79	1.78	4.51	3.00	5.88	11.01	1.27	2.57	5.46	11.13	20.90	37.55
2005	0.73	1.72	4.66	2.98	6.03	12.60	1.21	2.57	5.79	11.00	21.41	43.05
2006	0.80	1.87	4.74	3.18	6.10	12.02	1.26	2.57	5.67	11.59	21.39	41.18
2007	0.95	2.14	5.23	3.60	6.71	13.28	1.63	3.33	7.33	13.01	23.79	45.78
2008	1.49	3.85	10.57	4.05	8.35	15.48	1.86	3.89	9.27	14.91	29.30	54.57
2009	1.44	3.01	6.31	3.75	6.60	11.45	1.81	3.30	6.05	13.86	23.56	38.58
2010	1.16	2.39	5.16	3.86	6.97	12.40	1.83	3.57	6.92	14.12	24.82	43.25
2011	1.21	2.69	6.71	4.13	7.55	14.64	1.89	3.75	8.50	15.15	27.58	53.45
2012	1.08	2.25	5.39	4.10	7.39	13.25	1.85	3.40	6.81	14.99	26.19	45.37
2013	0.88	1.84	4.90	3.53	6.64	13.83	1.42	2.79	5.51	13.11	23.74	46.35
2014	0.91	2.16	5.74	3.72	7.66	15.68	1.28	2.71	6.22	13.80	26.56	52.28
2015	1.04	2.30	6.28	3.97	7.54	16.14	1.64	3.10	6.70	14.40	27.18	54.52
2016	1.24	2.83	7.26	4.31	8.03	15.06	2.05	3.83	6.80	15.38	28.50	51.87

Table 1: Summary Statistics (cont'd)

Panel D: Control Variable Summary

	mean	p50	sd	p10	p25	p75	p90
BETA	1.28	1.15	1.51	-0.23	0.48	1.96	3.02
SIZE	14.97	14.88	1.52	13.05	13.86	16.01	17.01
BM	0.45	0.35	0.41	0.10	0.20	0.60	0.94
MOM (%)	23.90	18.52	48.21	-25.58	-2.49	42.90	76.75
REV (%)	1.95	1.43	13.32	-12.63	-5.13	8.14	16.53
IVOL (%)	2.23	1.80	1.53	0.84	1.19	2.79	4.18
MAX (%)	2.16	1.87	12.77	-11.86	-4.44	8.30	16.41
RSKEW	0.24	0.19	1.28	-0.86	-0.21	0.63	1.35
RKURT	9.82	6.02	11.48	3.70	4.43	10.05	19.19
LN_ILLIQ	-7.50	-7.60	1.76	-9.68	-8.79	-6.30	-5.14
IV	0.43	0.38	0.21	0.22	0.28	0.52	0.71
IS (%)	-4.32	-4.07	6.51	-10.83	-6.91	-1.72	1.53
IK (%)	4.62	2.21	8.45	-0.67	0.82	5.23	12.09
RV_IV (%)	-1.40	-3.37	15.77	-16.25	-9.37	3.76	15.39
VTS (%)	-0.72	-0.05	5.12	-6.39	-2.63	2.08	4.16
dCIV (%)	-0.57	-0.41	9.06	-10.21	-4.58	3.63	8.87
dPIV (%)	-0.58	-0.48	9.04	-10.01	-4.57	3.53	8.71

Table 1: Summary Statistics (cont'd)

Panel E: Correlations

	VOV^{un}	VOV	VOV6M	VOV^{al}	BETA	SIZE	BM	MOM	REV	IVOL	MAX	RS
VOV^{un}	1.00											
VOV	0.76	1.00										
VOV6M	0.59	0.70	1.00									
VOV^{al}	0.74	0.96	0.69	1.00								
BETA	0.13	0.00	0.00	0.00	1.00							
SIZE	-0.26	-0.01	-0.03	-0.02	-0.10	1.00						
BM	-0.02	0.01	0.06	0.02	0.00	-0.09	1.00					
MOM	0.05	-0.03	-0.04	-0.03	0.09	-0.02	-0.14	1.00				
REV	-0.08	-0.07	-0.06	-0.07	0.00	0.01	0.02	-0.01	1.00			
IVOL	0.55	0.14	0.19	0.13	0.18	-0.39	-0.08	0.15	-0.04	1.00		
MAX	0.00	-0.01	0.00	-0.01	0.03	-0.07	0.02	-0.01	-0.02	0.10	1.00	
RS	0.08	0.06	0.07	0.06	0.02	-0.05	-0.03	0.27	0.10	0.09	0.11	1.00
RK	0.15	0.16	0.13	0.17	-0.01	-0.16	-0.06	0.03	0.01	0.13	0.02	0.24
DEMAND	-0.03	-0.01	0.00	-0.01	-0.04	-0.10	0.01	-0.03	0.03	-0.06	0.06	0.04
BID_ASK	0.15	0.23	0.21	0.26	-0.04	-0.38	0.12	-0.07	-0.02	-0.01	-0.02	0.03
IV	0.55	0.02	0.09	0.01	0.23	-0.47	-0.06	0.16	-0.02	0.76	-0.03	0.08
IS	-0.21	-0.08	-0.11	-0.08	-0.07	-0.01	-0.01	0.03	0.02	-0.13	-0.02	-0.03
IK	0.14	0.21	0.17	0.23	-0.03	-0.25	0.10	-0.08	-0.03	0.00	-0.02	0.00
RV_IV	0.28	0.25	0.27	0.26	0.15	0.04	-0.01	0.01	-0.08	0.57	0.15	0.02
VTS	-0.29	-0.07	-0.15	-0.07	-0.06	0.10	0.02	-0.01	0.04	-0.32	0.12	-0.03
dCIV	-0.05	-0.07	-0.01	-0.07	0.00	0.06	-0.03	0.04	0.08	-0.01	-0.35	-0.02
dPIV	-0.03	-0.06	0.01	-0.05	0.01	0.06	-0.03	0.04	0.05	0.00	-0.30	-0.02

	RK	DEMAND	BID_ASK	LN_ILLIQ	IV	IS	IK	RV_IV	VTS	dCIV	dPIV
RK	1.00										
DEMAND	0.05	1.00									
BID_ASK	0.08	0.02	1.00								
LN_ILLIQ	0.09	0.11	0.41	1.00							
IV	0.06	-0.03	-0.02	0.49	1.00						
IS	0.01	0.02	0.09	0.02	-0.23	1.00					
IK	0.07	0.06	0.51	0.27	-0.04	0.13	1.00				
RV_IV	0.05	-0.11	-0.03	-0.01	0.03	-0.06	0.02	1.00			
VTS	-0.03	0.04	-0.02	-0.15	-0.52	0.17	0.09	0.07	1.00		
dCIV	-0.01	-0.03	-0.06	-0.03	0.17	0.02	-0.11	-0.18	-0.50	1.00	
dPIV	-0.01	-0.02	-0.04	-0.03	0.17	-0.12	-0.10	-0.16	-0.50	0.79	1.00

Table 2: Firm-level cross-sectional regressions of delta-hedged call option returns

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged call option returns. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.018***	-0.020***	-0.018***	-0.019***	-0.019***	-0.018***	-0.020***
	(-4.20)	(-4.75)	(-4.15)	(-4.23)	(-4.43)	(-3.98)	(-4.57)
BETA		0.00041*					0.00026
		(1.88)					(1.17)
SIZE			0.00062***				0.00051***
			(3.68)				(3.46)
BM				-0.00075			-0.00032
				(-0.84)			(-0.41)
MOM					-0.00067		-0.00063
					(-1.28)		(-1.32)
REV						-0.00075	-0.00072
						(-0.43)	(-0.41)
R-squared	0.009	0.018	0.019	0.016	0.020	0.018	0.051

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.018***	-0.016***	-0.021***	-0.018***	-0.015***	-0.016***
	(-4.20)	(-3.99)	(-5.11)	(-3.95)	(-3.21)	(-4.03)
IVOL		-0.035				-0.036*
		(-1.63)				(-1.70)
MAX			0.00013			0.0020
			(0.069)			(1.04)
RS				-0.00055***		-0.00036***
				(-3.96)		(-3.23)
RK					-0.00013***	-0.00010***
					(-5.32)	(-4.72)
R-squared	0.009	0.023	0.020	0.015	0.017	0.045

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.018***	-0.018***	-0.017***	-0.019***	-0.020***
	(-4.20)	(-4.30)	(-4.08)	(-4.53)	(-4.80)
DEMAND		-0.019***			-0.017***
		(-4.29)			(-3.02)
BID_ASK			-0.0036		0.0046
			(-1.13)		(1.65)
LN_ILLIQ				-0.00065***	-0.00066***
				(-3.63)	(-3.62)
R-squared	0.009	0.016	0.018	0.021	0.035

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.018***	-0.016***	-0.019***	-0.020***	-0.027***	-0.017***	-0.021***	-0.027***
	(-4.20)	(-3.71)	(-4.67)	(-4.46)	(-7.32)	(-4.03)	(-5.26)	(-6.67)
IV		-0.010***						-0.0094***
		(-5.28)						(-5.13)
IS			-0.017***					-0.020***
			(-4.53)					(-5.84)
IK				0.0069**				0.0052*
				(2.13)				(1.69)
RV_IV					0.011***			0.0089***
					(7.85)			(5.22)
VTS						0.032***		0.0096**
						(6.26)		(1.97)
dCIV							-0.019***	-0.012***
							(-7.73)	(-4.19)
R-squared	0.009	0.036	0.020	0.016	0.021	0.025	0.022	0.083

Table 3: Firm-level cross-sectional regressions of delta-hedged put option returns

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged put option returns. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.022***	-0.023***	-0.022***	-0.024***	-0.024***	-0.022***	-0.025***
	(-4.97)	(-5.63)	(-5.02)	(-5.52)	(-5.74)	(-4.89)	(-5.98)
BETA		0.00025					0.00015
		(1.31)					(0.75)
SIZE			0.00089***				0.00077***
			(6.02)				(5.56)
BM				-0.00081			-0.00017
				(-0.93)			(-0.24)
MOM					-0.00056		-0.00054
					(-1.19)		(-1.24)
REV						-0.0016	-0.0017
						(-0.96)	(-0.99)
R-squared	0.010	0.020	0.022	0.017	0.020	0.019	0.053

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.022***	-0.019***	-0.024***	-0.023***	-0.020***	-0.019***
	(-4.97)	(-4.58)	(-6.03)	(-5.15)	(-4.29)	(-5.22)
IVOL		-0.077***				-0.073***
		(-3.52)				(-3.36)
MAX			-0.0028			-0.00027
			(-1.53)			(-0.15)
RS				-0.00069***		-0.00047***
				(-4.52)		(-3.98)
RK					-0.00014***	-0.00011***
					(-5.74)	(-4.89)
R-squared	0.010	0.025	0.020	0.017	0.019	0.047

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.022***	-0.022***	-0.021***	-0.023***	-0.024***
	(-4.97)	(-5.04)	(-4.73)	(-5.51)	(-5.72)
DEMAND		-0.036***			-0.052**
		(-3.24)			(-2.07)
BID_ASK			-0.0017		0.0077***
			(-0.74)		(3.00)
LN_ILLIQ				-0.00088***	-0.00096***
				(-5.60)	(-5.81)
R-squared	0.010	0.018	0.018	0.023	0.037

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.022***	-0.020***	-0.020***	-0.022***	-0.031***	-0.022***	-0.024***	-0.026***
	(-4.97)	(-4.85)	(-4.39)	(-4.82)	(-8.08)	(-5.25)	(-5.84)	(-6.90)
IV		-0.014***						-0.012***
		(-7.54)						(-6.52)
IS			0.026***					0.021***
			(8.17)					(6.60)
IK				0.0015				-0.00032
				(0.54)				(-0.12)
RV_IV					0.012***			0.010***
					(8.28)			(6.07)
VTS						0.031***		0.014***
						(6.36)		(2.90)
dCIV							-0.0026	0.0047*
							(-1.09)	(1.68)
R-squared	0.010	0.040	0.023	0.017	0.022	0.025	0.021	0.083

Table 4: Firm-level cross-sectional regressions of delta-hedged gains

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged gains. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.55***	-0.62***	-0.54***	-0.58***	-0.61***	-0.56***	-0.63***
	(-3.34)	(-4.11)	(-3.26)	(-3.47)	(-3.96)	(-3.23)	(-4.11)
BETA		0.022***					0.011
		(3.02)					(1.54)
SIZE			-0.018**				-0.018**
			(-2.15)				(-2.16)
BM				-0.032			-0.017
				(-0.86)			(-0.67)
MOM					0.0076		0.0046
					(0.29)		(0.20)
REV						-0.049	-0.042
						(-0.73)	(-0.65)
R-squared	0.007	0.015	0.022	0.014	0.023	0.015	0.053

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.55***	-0.73***	-0.63***	-0.52***	-0.44**	-0.63***
	(-3.34)	(-5.09)	(-4.06)	(-3.00)	(-2.49)	(-4.50)
IVOL		2.25***				1.91***
		(3.20)				(2.74)
MAX			-0.050			-0.052
			(-0.65)			(-0.67)
RS				-0.020***		-0.017***
				(-3.19)		(-2.91)
RK					-0.0039***	-0.0035***
					(-4.66)	(-4.56)
R-squared	0.007	0.015	0.016	0.012	0.013	0.033

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.55***	-0.54***	-0.61***	-0.51***	-0.51***
	(-3.34)	(-3.24)	(-3.64)	(-3.17)	(-2.98)
DEMAND		1.59			1.71
		(0.88)			(0.87)
BID_ASK			0.12		0.091
			(0.73)		(0.81)
LN_ILLIQ				0.014	0.017**
				(1.53)	(2.13)
R-squared	0.007	0.011	0.020	0.025	0.035

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.55***	-0.59***	-0.59***	-0.65***	-0.78***	-0.60***	-0.71***	-0.96***
	(-3.34)	(-4.04)	(-3.81)	(-3.88)	(-5.48)	(-4.03)	(-4.91)	(-6.92)
IV		0.089						0.12**
		(1.62)						(2.24)
IS			-0.48***					-0.41***
			(-3.93)					(-3.83)
IK				0.39***				0.33***
				(3.37)				(2.74)
RV_IV					0.26***			0.21***
					(4.41)			(3.34)
VTS						0.49***		0.41***
						(2.85)		(2.72)
dCIV							-0.46***	-0.33***
							(-5.93)	(-3.85)
R-squared	0.007	0.018	0.012	0.014	0.014	0.016	0.016	0.048

Table 5: Firm-level cross-sectional regressions of delta-hedged gains scaled by the initial option price

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged gains scaled by the initial option price. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) *t*-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.27***	-0.29***	-0.27***	-0.29***	-0.28***	-0.26***	-0.30***
	(-4.36)	(-4.82)	(-4.27)	(-4.45)	(-4.50)	(-4.15)	(-4.58)
BETA		0.011***					0.0063***
		(5.16)					(2.85)
SIZE			-0.0039				-0.0030
			(-1.64)				(-1.29)
BM				-0.010			-0.0077
				(-1.03)			(-0.86)
MOM					-0.0035		-0.0053
					(-0.41)		(-0.74)
REV						-0.017	-0.017
						(-0.82)	(-0.79)
R-squared	0.008	0.016	0.018	0.015	0.016	0.015	0.044

Panel B: Return Distribution Characteristics						
	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.27***	-0.31***	-0.30***	-0.27***	-0.24***	-0.29***
	(-4.36)	(-5.22)	(-4.93)	(-4.34)	(-3.83)	(-4.89)
IVOL		0.75***				0.60***
		(3.57)				(2.87)
MAX			0.020			0.020
			(0.77)			(0.81)
RS				-0.0058***		-0.0044***
				(-3.33)		(-2.90)
RK					-0.0013***	-0.0012***
					(-5.61)	(-5.59)
R-squared	0.008	0.017	0.017	0.013	0.014	0.034

Panel C: Limits to Arbitrage					
	(1)	(2)	(3)	(4)	(5)
VOV	-0.27***	-0.26***	-0.28***	-0.27***	-0.26***
	(-4.36)	(-4.28)	(-4.78)	(-4.32)	(-4.55)
DEMAND		-0.24***			-0.18*
		(-3.34)			(-1.96)
BID_ASK			0.025		0.024
			(0.59)		(0.56)
LN_ILLIQ				0.0027	0.0038
				(1.16)	(1.47)
R-squared	0.008	0.014	0.019	0.019	0.036

Panel D:Option-based Characteristics								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.27***	-0.26***	-0.28***	-0.28***	-0.36***	-0.25***	-0.31***	-0.38***
	(-4.36)	(-4.03)	(-4.80)	(-4.44)	(-6.28)	(-3.44)	(-5.25)	(-6.23)
IV		0.017						0.031
		(0.78)						(1.33)
IS			-0.22***					-0.19***
			(-5.93)					(-4.72)
IK				0.074**				0.047
				(1.98)				(1.23)
RV_IV					0.11***			0.094***
					(5.82)			(4.82)
VTS						0.21***		0.13*
						(3.47)		(1.79)
dCIV							-0.23***	-0.17***
							(-7.19)	(-4.48)
R-squared	0.008	0.020	0.016	0.015	0.017	0.016	0.017	0.057

Table 6: Firm-level cross-sectional regressions of delta-hedged gains scaled by the absolute value of the securities involved

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged gains scaled by the absolute value of the securities involved. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.041***	-0.044***	-0.041***	-0.043***	-0.043***	-0.040***	-0.044***
	(-4.11)	(-4.58)	(-4.08)	(-4.12)	(-4.32)	(-3.89)	(-4.41)
BETA		0.00082*					0.00052
		(1.67)					(1.05)
SIZE			0.0015***				0.0013***
			(4.02)				(3.78)
BM				-0.0016			-0.00057
				(-0.79)			(-0.33)
MOM					-0.0017		-0.0016
					(-1.47)		(-1.50)
REV						-0.0013	-0.0011
						(-0.32)	(-0.29)
R-squared	0.009	0.019	0.020	0.017	0.021	0.019	0.053

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.041***	-0.036***	-0.047***	-0.039***	-0.034***	-0.035***
	(-4.11)	(-3.83)	(-4.98)	(-3.83)	(-3.13)	(-3.85)
IVOL		-0.094*				-0.094*
		(-1.92)				(-1.96)
MAX			0.00011			0.0044
			(0.025)			(1.03)
RS				-0.0013***		-0.00084***
				(-4.04)		(-3.36)
RK					-0.00030***	-0.00023***
					(-5.31)	(-4.68)
R-squared	0.009	0.024	0.021	0.016	0.018	0.047

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.041***	-0.042***	-0.039***	-0.044***	-0.045***
	(-4.11)	(-4.21)	(-3.94)	(-4.47)	(-4.71)
DEMAND		-0.042***			-0.036***
		(-4.47)			(-3.20)
BID_ASK			-0.0096		0.0097
			(-1.35)		(1.58)
LN_ILLIQ				-0.0016***	-0.0016***
				(-3.93)	(-3.83)
R-squared	0.009	0.017	0.018	0.022	0.036

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.041***	-0.035***	-0.044***	-0.045***	-0.060***	-0.039***	-0.048***	-0.061***
	(-4.11)	(-3.64)	(-4.61)	(-4.30)	(-7.03)	(-4.00)	(-5.11)	(-6.41)
IV		-0.025***						-0.023***
		(-5.47)						(-5.43)
IS			-0.037***					-0.044***
			(-4.17)					(-5.53)
IK				0.015**				0.011
				(2.02)				(1.61)
RV_IV					0.026***			0.020***
					(7.74)			(5.15)
VTS						0.073***		0.020*
						(6.10)		(1.85)
dCIV							-0.042***	-0.026***
							(-7.58)	(-4.11)
R-squared	0.009	0.039	0.021	0.017	0.022	0.027	0.023	0.088

Table 7: Firm-level cross-sectional regressions of monthly rebalanced delta-hedged call option returns

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of monthly rebalanced delta-hedged call option returns. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) *t*-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.026***	-0.026***	-0.025***	-0.028***	-0.026***	-0.025***	-0.027***
	(-4.27)	(-4.41)	(-3.93)	(-4.51)	(-4.06)	(-3.92)	(-4.27)
BETA		-0.00020					-0.00029
		(-0.62)					(-0.90)
SIZE			0.000080				-0.00026
			(0.32)				(-0.97)
BM				0.00041			0.00014
				(0.29)			(0.098)
MOM					-0.0016		-0.0013
					(-1.53)		(-1.35)
REV						-0.00070	-0.0019
						(-0.18)	(-0.49)
R-squared	0.006	0.017	0.013	0.013	0.018	0.015	0.049

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.026***	-0.023***	-0.026***	-0.025***	-0.024***	-0.024***
	(-4.27)	(-3.30)	(-4.19)	(-3.93)	(-3.64)	(-3.67)
IVOL		-0.038				-0.027
		(-0.96)				(-0.74)
MAX			-0.0014			-0.00092
			(-0.34)			(-0.22)
RS				-0.00065*		-0.00044
				(-1.85)		(-1.36)
RK					-0.000085**	-0.000046
					(-2.27)	(-1.24)
R-squared	0.006	0.019	0.015	0.012	0.013	0.037

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.026***	-0.026***	-0.024***	-0.026***	-0.024***
	(-4.27)	(-4.24)	(-3.95)	(-4.21)	(-3.97)
DEMAND		-0.017			-0.023
		(-1.45)			(-1.06)
BID_ASK			-0.0084		-0.0075
			(-1.50)		(-0.98)
LN_ILLIQ				-0.00041*	-0.00023
				(-1.75)	(-0.76)
R-squared	0.006	0.010	0.013	0.013	0.025

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.026***	-0.023***	-0.027***	-0.029***	-0.029***	-0.022***	-0.026***	-0.024***
	(-4.27)	(-3.44)	(-4.60)	(-4.87)	(-4.92)	(-3.11)	(-4.38)	(-3.63)
IV		-0.0062*						-0.0015
		(-1.90)						(-0.39)
IS			-0.020***					-0.021***
			(-3.27)					(-3.91)
IK				0.010*				0.0049
				(1.90)				(0.87)
RV_IV					0.0037			0.00030
					(1.56)			(0.12)
VTS						0.047***		0.037***
						(5.39)		(4.35)
dCIV							-0.027***	-0.015***
							(-6.02)	(-3.19)
R-squared	0.006	0.025	0.014	0.011	0.013	0.017	0.015	0.060

Table 8: Firm-level cross-sectional regressions of straddle returns

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of straddle returns. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.065***	-0.063***	-0.063***	-0.069***	-0.065***	-0.063***	-0.066***
	(-5.47)	(-5.30)	(-4.94)	(-5.95)	(-5.34)	(-5.16)	(-5.31)
BETA		-0.00073					-0.00078
		(-1.10)					(-1.31)
SIZE			0.00061				-0.00036
			(0.99)				(-0.58)
BM				0.00088			0.00043
				(0.30)			(0.14)
MOM					-0.0030		-0.0027
					(-1.28)		(-1.18)
REV						-0.0011	-0.0032
						(-0.13)	(-0.37)
R-squared	0.006	0.017	0.015	0.014	0.018	0.016	0.050

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.065***	-0.055***	-0.063***	-0.065***	-0.063***	-0.060***
	(-5.47)	(-3.49)	(-5.22)	(-5.36)	(-5.17)	(-4.49)
IVOL		-0.17**				-0.11
		(-2.00)				(-1.62)
MAX			-0.0067			-0.0042
			(-0.74)			(-0.47)
RS				-0.0014*		-0.00095
				(-1.72)		(-1.27)
RK					-0.00014*	-0.000048
					(-1.71)	(-0.61)
R-squared	0.006	0.020	0.015	0.013	0.014	0.037

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.065***	-0.064***	-0.060***	-0.067***	-0.061***
	(-5.47)	(-5.42)	(-5.04)	(-5.44)	(-5.29)
DEMAND		0.0071			0.0027
		(0.22)			(0.055)
BID_ASK			-0.019*		-0.015
			(-1.65)		(-0.94)
LN_ILLIQ				-0.0013**	-0.00087
				(-2.23)	(-1.21)
R-squared	0.006	0.011	0.014	0.017	0.028

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.065***	-0.056***	-0.061***	-0.071***	-0.068***	-0.058***	-0.060***	-0.051***
	(-5.47)	(-4.11)	(-5.00)	(-6.08)	(-5.43)	(-4.00)	(-4.97)	(-3.49)
IV		-0.020***						-0.0057
		(-2.98)						(-0.68)
IS			0.020*					0.017
			(1.73)					(1.52)
IK				0.015				-0.0041
				(1.33)				(-0.31)
RV_IV					0.0081			0.0018
					(1.57)			(0.34)
VTS						0.10***		0.078***
						(5.72)		(3.45)
dCIV							-0.037***	-0.014
							(-4.33)	(-1.25)
R-squared	0.006	0.027	0.015	0.012	0.016	0.018	0.014	0.062

Table 9: Firm-level cross-sectional regressions on VOV6M

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged call option returns on VOV6M. The volatility of volatility (VOV6M) is defined as the standard deviation of the ATM 180-day IV6M scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.033***	-0.035***	-0.030***	-0.033***	-0.035***	-0.033***	-0.033***
	(-5.28)	(-5.60)	(-4.59)	(-5.06)	(-5.36)	(-4.97)	(-4.72)
BETA		0.00042*					0.00027
		(1.89)					(1.16)
SIZE			0.00063***				0.00054***
			(3.80)				(3.61)
BM				-0.00066			-0.00019
				(-0.74)			(-0.25)
MOM					-0.00070		-0.00069
					(-1.28)		(-1.35)
REV						-0.00072	-0.00059
						(-0.40)	(-0.34)
R-squared	0.008	0.017	0.018	0.015	0.019	0.017	0.050

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.033***	-0.029***	-0.038***	-0.032***	-0.028***	-0.028***
	(-5.28)	(-4.75)	(-6.00)	(-4.92)	(-4.05)	(-4.39)
IVOL		-0.037*				-0.038*
		(-1.71)				(-1.81)
MAX			-0.000060			0.0018
			(-0.030)			(0.94)
RS				-0.00055***		-0.00037***
				(-4.02)		(-3.26)
RK					-0.00013***	-0.00011***
					(-5.53)	(-4.96)
R-squared	0.008	0.021	0.019	0.014	0.017	0.044

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.033***	-0.033***	-0.031***	-0.031***	-0.032***
	(-5.28)	(-5.32)	(-4.95)	(-4.81)	(-5.02)
DEMAND		-0.021***			-0.019***
		(-3.91)			(-2.65)
BID_ASK			-0.0036		0.0044
			(-1.15)		(1.56)
LN_ILLIQ				-0.00065***	-0.00065***
				(-3.64)	(-3.60)
R-squared	0.008	0.015	0.017	0.020	0.035

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.033***	-0.029***	-0.035***	-0.036***	-0.046***	-0.027***	-0.034***	-0.043***
	(-5.28)	(-4.89)	(-5.85)	(-5.86)	(-8.12)	(-4.66)	(-5.49)	(-8.36)
IV		-0.011***						-0.0095***
		(-5.39)						(-5.24)
IS			-0.017***					-0.020***
			(-4.45)					(-5.70)
IK				0.0066**				0.0051*
				(2.04)				(1.69)
RV_IV					0.011***			0.0087***
					(7.80)			(5.15)
VTS						0.032***		0.0098**
						(6.54)		(1.99)
dCIV							-0.017***	-0.010***
							(-7.25)	(-3.61)
R-squared	0.008	0.034	0.020	0.015	0.021	0.023	0.021	0.081

Table 10: Firm-level cross-sectional regressions on the alternative VOV

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged call option returns until the end of month. The alternative VOV is defined as the difference between the natural log of the maximum of IV and the natural log of the minimum of IV in month t and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.0057***	-0.0061***	-0.0055***	-0.0058***	-0.0058***	-0.0056***	-0.0059***
	(-4.06)	(-4.59)	(-3.92)	(-4.01)	(-4.14)	(-3.84)	(-4.13)
BETA		0.00040*					0.00024
		(1.84)					(1.11)
SIZE			0.00062***				0.00051***
			(3.69)				(3.47)
BM				-0.00073			-0.00030
				(-0.82)			(-0.40)
MOM					-0.00071		-0.00070
					(-1.34)		(-1.41)
REV						-0.00077	-0.00074
						(-0.44)	(-0.42)
R-squared	0.008	0.018	0.019	0.016	0.019	0.018	0.051

Panel B: Return Distribution Characteristics						
	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.0057***	-0.0051***	-0.0064***	-0.0055***	-0.0047***	-0.0048***
	(-4.06)	(-3.88)	(-4.89)	(-3.78)	(-3.12)	(-3.77)
IVOL		-0.035				-0.035*
		(-1.63)				(-1.66)
MAX			0.00024			0.0021
			(0.12)			(1.11)
RS				-0.00054***		-0.00037***
				(-3.91)		(-3.29)
RK					-0.00013***	-0.00011***
					(-5.38)	(-4.79)
R-squared	0.008	0.022	0.019	0.015	0.017	0.045

Panel C: Limits to Arbitrage					
	(1)	(2)	(3)	(4)	(5)
VOV	-0.0057***	-0.0058***	-0.0054***	-0.0059***	-0.0062***
	(-4.06)	(-4.12)	(-3.78)	(-4.22)	(-4.49)
DEMAND		-0.018***			-0.017***
		(-4.53)			(-3.02)
BID_ASK			-0.0035		0.0048*
			(-1.08)		(1.69)
LN_ILLIQ				-0.00065***	-0.00067***
				(-3.63)	(-3.68)
R-squared	0.008	0.016	0.018	0.021	0.035

Panel D:Option-based Characteristics								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.0057***	-0.0048***	-0.0061***	-0.0064***	-0.0087***	-0.0054***	-0.0066***	-0.0088***
	(-4.06)	(-3.66)	(-4.56)	(-4.47)	(-7.38)	(-3.93)	(-5.01)	(-6.92)
IV		-0.011***						-0.0094***
		(-5.38)						(-5.11)
IS			-0.017***					-0.020***
			(-4.49)					(-5.84)
IK				0.0071**				0.0058*
				(2.22)				(1.90)
RV_IV					0.012***			0.0091***
					(8.09)			(5.31)
VTS						0.033***		0.0095*
						(6.43)		(1.94)
dCIV							-0.019***	-0.012***
							(-7.92)	(-4.21)
R-squared	0.008	0.035	0.020	0.016	0.021	0.024	0.022	0.082

Table 11: Univariate portfolios sorted on VOV

This table reports the average return of holding delta-hedged call option portfolios on volatility of volatility (VOV). At the end of each month, we rank the delta-hedged option portfolios into 5 deciles based on VOV and then calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low " row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean. The risk-adjusted average returns are also reported in the column 3 to column 6. The risk factors including Fama and French (1993) three factors (MKT, SMB, HML), Carhart (1997) momentum factor (UMD) and Fama and French (2015) five factors (RMW, CMA) are obtained from the Kenneth R. French Data Library. The sample period is from January 1996 to April 2016. The robust Newey and West (1987) t-statistics of the high-row portfolios are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Raw return	CAPM alpha	Three-Factor alpha	Four-Factor alpha	Five-Factor alpha
Low	-0.24	-0.22	-0.23	-0.26	-0.21
2	-0.24	-0.22	-0.22	-0.26	-0.21
3	-0.24	-0.22	-0.23	-0.25	-0.22
4	-0.32	-0.30	-0.31	-0.33	-0.31
High	-0.40	-0.38	-0.39	-0.41	-0.39
High-Low	-0.16***	-0.16***	-0.17***	-0.15**	-0.18***
	(-2.90)	(-2.83)	(-3.06)	(-2.60)	(-3.23)

Table 12: Firm-level cross-sectional regressions of VOV

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of VOV. All independent variables are winsorized each month at the 0.5% level. The sample period is January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
VOV	0.44***																	0.40***
	(19.9)																	(21.9)
BETA		-0.0025***																-0.00068***
		(-5.10)																(-4.79)
SIZE			-0.0047***															-0.0012*
			(-6.04)															(-1.95)
BM				0.0073***														0.0016***
				(5.70)														(5.24)
MOM					-0.0057***													-0.0029***
					(-4.39)													(-6.48)
REV						0.0055**												0.0016
						(2.55)												(1.19)
IVOL							-0.091*											-0.12**
							(-1.69)											(-2.02)
MAX								0.0017										0.0034***
								(0.84)										(2.67)
RS									0.0034***									0.0017***
									(10.4)									(12.9)
RK										0.00049***								0.00026***
										(14.4)								(14.1)
LN_ILLIQ											0.0036***							0.00036
											(5.61)							(0.68)
IV												0.032***						-0.014**
												(6.68)						(-2.59)
IS													-0.00068					-0.0038
													(-0.13)					(-1.42)
IK														0.070***				0.051***
														(15.4)				(15.3)
RV_IV															-0.044***			-0.028***
															(-5.49)			(-5.24)
VTS																-0.20***		-0.100***
																(-10.8)		(-14.2)
dCIV																	0.022***	0.0014
																	(9.27)	(0.63)
R-squared	0.196	0.003	0.015	0.004	0.003	0.002	0.005	0.002	0.005	0.009	0.015	0.015	0.005	0.018	0.021	0.051	0.008	0.253

Table 13: Bivariate portfolios sorted on control variables and VOV

This table reports the average return of holding delta-hedged call option portfolios on volatility of volatility (VOV). At the end of each month, we rank the delta-hedged option portfolios into 5 deciles, based on each control variable, and then sequentially rank each decile into another 5 deciles, based on VOV. Finally, we calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low" row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. The robust Newey and West (1987) *t*-statistics of the high-row portfolios are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Low	2	3	4	High	High-Low	t
BETA	-0.24	-0.21	-0.28	-0.3	-0.42	-0.18***	(-3.44)
SIZE	-0.25	-0.22	-0.26	-0.3	-0.41	-0.15***	(-2.91)
BM	-0.2	-0.22	-0.24	-0.26	-0.4	-0.20***	(-3.72)
MOM	-0.23	-0.21	-0.25	-0.28	-0.39	-0.16***	(-3.03)
REV	-0.22	-0.25	-0.25	-0.3	-0.42	-0.20***	(-3.69)
IVOL	-0.24	-0.25	-0.26	-0.3	-0.4	-0.16***	(-3.13)
MAX	-0.21	-0.24	-0.27	-0.32	-0.41	-0.19***	(-4.02)
RS	-0.22	-0.24	-0.23	-0.3	-0.38	-0.16***	(-2.98)
RK	-0.22	-0.26	-0.23	-0.28	-0.38	-0.16***	(-2.90)
DEMAND	-0.23	-0.24	-0.26	-0.3	-0.42	-0.19***	(-3.83)
BID_ASK	-0.24	-0.24	-0.26	-0.32	-0.39	-0.16***	(-2.79)
LN_ILLIQ	-0.24	-0.23	-0.26	-0.31	-0.41	-0.18***	(-3.42)
IV	-0.25	-0.24	-0.26	-0.29	-0.4	-0.15***	(-3.11)
IS	-0.25	-0.23	-0.23	-0.33	-0.4	-0.15***	(-2.79)
IK	-0.25	-0.22	-0.25	-0.32	-0.4	-0.15***	(-2.86)
RV_IV	-0.18	-0.24	-0.29	-0.29	-0.45	-0.27***	(-6.05)
VTS	-0.21	-0.26	-0.26	-0.31	-0.4	-0.19***	(-3.91)
dCIV	-0.25	-0.22	-0.26	-0.29	-0.41	-0.16***	(-3.80)

Cross Section of Option Returns and Volatility-of-Volatility

Internet Appendix

Table IA.1: Firm-level cross-sectional regressions after controlling for VOL-of-VOL in Cao et al. (2017)

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged call option returns. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV scaled its mean and the details of control variable construction are provided in Appendix A.2. In line with Cao et al. (2017), we obtain estimates of daily volatility for each stock in each month by applying from the EGARCH (1,1) model to a rolling window of past 12-month daily stock returns and VOL-of-VOL is measured as the standard deviation of percentage change in the daily realized volatility over one month. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) *t*-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	(1)	(2)	(3)
VOV	-0.018***		-0.017***
	(-4.20)		(-3.57)
VOL-of-VOL		-4.2e-06***	-3.7e-06**
		(-2.83)	(-2.49)

Table IA.2: Firm-level cross-sectional regressions on the unscaled VOV

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged call option returns. The unscaled volatility of volatility (unscaled VOV) is defined as the standard deviation of the ATM 30-day IV and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.055***	-0.061***	-0.053***	-0.055***	-0.057***	-0.056***	-0.063***
	(-5.49)	(-6.55)	(-5.03)	(-5.46)	(-5.54)	(-5.87)	(-6.31)
BETA		0.00059**					0.00041*
		(2.50)					(1.67)
SIZE			0.00033*				0.00023
			(1.84)				(1.45)
BM				-0.00098			-0.00052
				(-1.12)			(-0.68)
MOM					-0.00040		-0.00037
					(-0.73)		(-0.75)
REV						-0.00083	-0.00080
						(-0.47)	(-0.46)
R-squared	0.018	0.027	0.027	0.025	0.030	0.027	0.059

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.055***	-0.058***	-0.063***	-0.051***	-0.048***	-0.058***
	(-5.49)	(-6.63)	(-6.62)	(-4.80)	(-4.37)	(-6.42)
IVOL		0.016				0.013
		(0.79)				(0.67)
MAX			0.00031			0.0014
			(0.16)			(0.74)
RS				-0.00051***		-0.00034***
				(-3.69)		(-3.09)
RK					-0.00012***	-0.000098***
					(-4.64)	(-4.36)
R-squared	0.018	0.029	0.030	0.025	0.026	0.052

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.055***	-0.055***	-0.055***	-0.053***	-0.053***
	(-5.49)	(-5.60)	(-5.49)	(-5.29)	(-5.31)
DEMAND		-0.021***			-0.018***
		(-3.75)			(-2.89)
BID_ASK			-0.0030		0.0034
			(-0.97)		(1.28)
LN_ILLIQ				-0.00042**	-0.00038**
				(-2.22)	(-1.98)
R-squared	0.018	0.025	0.027	0.030	0.044

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.055***	-0.031***	-0.059***	-0.057***	-0.067***	-0.048***	-0.059***	-0.056***
	(-5.49)	(-3.22)	(-6.26)	(-5.57)	(-7.58)	(-4.91)	(-5.77)	(-6.34)
IV		-0.0081***						-0.0049**
		(-3.96)						(-2.49)
IS			-0.019***					-0.020***
			(-5.32)					(-6.07)
IK				0.0081**				0.0047
				(2.57)				(1.56)
RV_IV					0.012***			0.0091***
					(7.96)			(5.37)
VTS						0.030***		0.0099**
						(6.42)		(2.03)
dCIV							-0.021***	-0.013***
							(-8.22)	(-4.70)
R-squared	0.018	0.039	0.030	0.026	0.031	0.031	0.032	0.085

Table IA.3: Firm-level cross-sectional regressions on alternative implied skewness and kurtosis based on Bakshi et al. (2003) method

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions on alternative implied skewness and kurtosis based on Bakshi et al. (2003) method. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) *t*-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	(1)	(2)	(3)	(4)
VOV	-0.021**	-0.020**	-0.021**	-0.023***
	(-2.22)	(-2.13)	(-2.20)	(-3.23)
IV				-0.0042
				(-1.42)
IS		-0.00100**		-0.00065
		(-2.32)		(-1.64)
IK			-0.00029	-0.00065**
			(-0.93)	(-2.01)
RV_IV				0.0084***
				(3.82)
VTS				0.012
				(1.22)
dCIV				-0.0079
				(-1.63)
R-squared	0.032	0.046	0.042	0.172

Table IA.4: Bivariate portfolios sorted on control variables and the VOV: risk-adjusted average returns, adjusted by the CAPM model

This table reports the risk-adjusted average return of holding delta-hedged call option portfolios on Volatility of volatility (VOV), adjusted by the CAPM model. At the end of each month, we rank the delta-hedged option portfolios into 5 deciles, based on each control variable, and then sequentially rank each decile into another 5 deciles, based on VOV. Finally, we calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low " row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Low	2	3	4	High	High-Low	t
BETA	-0.23	-0.18	-0.26	-0.28	-0.40	-0.17***	(-3.40)
SIZE	-0.24	-0.20	-0.23	-0.29	-0.39	-0.15***	(-2.82)
BM	-0.19	-0.20	-0.22	-0.24	-0.39	-0.20***	(-3.67)
MOM	-0.22	-0.18	-0.23	-0.26	-0.37	-0.16***	(-2.97)
REV	-0.21	-0.23	-0.23	-0.28	-0.40	-0.19***	(-3.66)
IVOL	-0.22	-0.22	-0.24	-0.29	-0.38	-0.16***	(-3.08)
MAX	-0.19	-0.21	-0.24	-0.31	-0.39	-0.20***	(-3.99)
RS	-0.20	-0.22	-0.21	-0.27	-0.37	-0.16***	(-2.93)
RK	-0.21	-0.24	-0.21	-0.25	-0.36	-0.16***	(-2.80)
DEMAND	-0.21	-0.22	-0.24	-0.28	-0.40	-0.19***	(-3.83)
BID_ASK	-0.22	-0.22	-0.24	-0.29	-0.37	-0.15***	(-2.66)
LN_ILLIQ	-0.22	-0.21	-0.24	-0.28	-0.39	-0.17***	(-3.37)
IV	-0.23	-0.22	-0.24	-0.28	-0.38	-0.15***	(-3.09)
IS	-0.23	-0.21	-0.21	-0.32	-0.38	-0.14***	(-2.66)
IK	-0.23	-0.20	-0.24	-0.30	-0.38	-0.15***	(-2.80)
RV_IV	-0.16	-0.21	-0.28	-0.27	-0.43	-0.27***	(-6.06)
VTS	-0.20	-0.24	-0.24	-0.29	-0.38	-0.18***	(-3.86)
dCIV	-0.23	-0.20	-0.24	-0.27	-0.39	-0.16***	(-3.70)

Table IA.5: Bivariate portfolios sorted on control variables and the VOV: risk-adjusted average returns, adjusted by the three-factor model

This table reports the risk-adjusted average return of holding delta-hedged call option portfolios on Volatility of volatility (VOV), adjusted by the three-factor model. At the end of each month, we rank the delta-hedged option portfolios into 5 deciles, based on each control variable, and then sequentially rank each decile into another 5 deciles, based on VOV. Finally, we calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low" row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Low	2	3	4	High	High-Low	t
BETA	-0.23	-0.19	-0.27	-0.29	-0.41	-0.18***	(-3.37)
SIZE	-0.24	-0.21	-0.24	-0.29	-0.40	-0.15***	(-3.10)
BM	-0.19	-0.21	-0.23	-0.25	-0.40	-0.20***	(-3.81)
MOM	-0.22	-0.19	-0.24	-0.27	-0.38	-0.16***	(-3.13)
REV	-0.21	-0.23	-0.24	-0.29	-0.40	-0.19***	(-3.63)
IVOL	-0.23	-0.23	-0.24	-0.30	-0.38	-0.16***	(-3.06)
MAX	-0.20	-0.22	-0.25	-0.31	-0.40	-0.20***	(-4.15)
RS	-0.21	-0.23	-0.21	-0.29	-0.37	-0.16***	(-3.03)
RK	-0.21	-0.24	-0.21	-0.27	-0.37	-0.16***	(-2.86)
DEMAND	-0.21	-0.23	-0.25	-0.29	-0.41	-0.19***	(-4.00)
BID_ASK	-0.22	-0.23	-0.25	-0.30	-0.38	-0.16***	(-2.93)
LN_ILLIQ	-0.23	-0.22	-0.24	-0.29	-0.40	-0.17***	(-3.56)
IV	-0.24	-0.22	-0.24	-0.28	-0.39	-0.16***	(-3.23)
IS	-0.24	-0.22	-0.21	-0.32	-0.39	-0.15***	(-2.86)
IK	-0.23	-0.20	-0.24	-0.31	-0.39	-0.15***	(-2.93)
RV_IV	-0.16	-0.22	-0.28	-0.28	-0.43	-0.27***	(-6.07)
VTS	-0.20	-0.25	-0.24	-0.30	-0.39	-0.19***	(-3.86)
dCIV	-0.24	-0.21	-0.25	-0.28	-0.39	-0.16***	(-3.56)

Table IA.6: Bivariate portfolios sorted on control variables and the VOV: risk-adjusted average returns, adjusted by the four-factor model

This table reports the risk-adjusted average return of holding delta-hedged call option portfolios on Volatility of volatility (VOV), adjusted by the four-factor model. At the end of each month, we rank the delta-hedged option portfolios into 5 deciles, based on each control variable, and then sequentially rank each decile into another 5 deciles, based on VOV. Finally, we calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low" row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Low	2	3	4	High	High-Low	t
BETA	-0.26	-0.22	-0.30	-0.31	-0.42	-0.16***	(-2.97)
SIZE	-0.27	-0.24	-0.26	-0.32	-0.41	-0.14***	(-2.66)
BM	-0.23	-0.24	-0.26	-0.28	-0.41	-0.18***	(-3.40)
MOM	-0.25	-0.22	-0.27	-0.29	-0.40	-0.15***	(-2.76)
REV	-0.24	-0.26	-0.27	-0.31	-0.42	-0.17***	(-3.25)
IVOL	-0.26	-0.26	-0.27	-0.32	-0.40	-0.14**	(-2.58)
MAX	-0.23	-0.25	-0.27	-0.33	-0.42	-0.19***	(-3.75)
RS	-0.24	-0.25	-0.24	-0.31	-0.39	-0.14**	(-2.50)
RK	-0.25	-0.27	-0.24	-0.29	-0.39	-0.14**	(-2.37)
DEMAND	-0.25	-0.26	-0.27	-0.31	-0.42	-0.18***	(-3.56)
BID_ASK	-0.25	-0.26	-0.27	-0.33	-0.40	-0.15**	(-2.56)
LN_ILLIQ	-0.26	-0.25	-0.27	-0.31	-0.42	-0.16***	(-3.08)
IV	-0.27	-0.26	-0.27	-0.30	-0.41	-0.14***	(-2.91)
IS	-0.27	-0.26	-0.23	-0.35	-0.40	-0.14**	(-2.43)
IK	-0.27	-0.24	-0.27	-0.33	-0.40	-0.14**	(-2.53)
RV_IV	-0.19	-0.25	-0.31	-0.30	-0.45	-0.26***	(-5.83)
VTS	-0.23	-0.28	-0.27	-0.32	-0.40	-0.17***	(-3.30)
dCIV	-0.27	-0.24	-0.27	-0.30	-0.41	-0.15***	(-3.31)

Table IA.7: Bivariate portfolios sorted on control variables and the VOV: risk-adjusted average returns, adjusted by the five-factor model

This table reports the risk-adjusted average return of holding delta-hedged call option portfolios on Volatility of volatility (VOV), adjusted by the five-factor model. At the end of each month, we rank the delta-hedged option portfolios into 5 deciles, based on each control variable, and then sequentially rank each decile into another 5 deciles, based on VOV. Finally, we calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low" row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Low	2	3	4	High	High-Low	t
BETA	-0.22	-0.17	-0.27	-0.29	-0.41	-0.18***	(-3.34)
SIZE	-0.23	-0.19	-0.23	-0.31	-0.39	-0.16***	(-2.97)
BM	-0.19	-0.19	-0.23	-0.25	-0.39	-0.21***	(-3.49)
MOM	-0.21	-0.18	-0.23	-0.27	-0.38	-0.17***	(-3.09)
REV	-0.20	-0.22	-0.23	-0.30	-0.40	-0.20***	(-3.48)
IVOL	-0.22	-0.23	-0.25	-0.29	-0.39	-0.17***	(-3.18)
MAX	-0.19	-0.21	-0.24	-0.31	-0.40	-0.22***	(-4.14)
RS	-0.20	-0.22	-0.21	-0.29	-0.38	-0.18***	(-3.11)
RK	-0.21	-0.22	-0.21	-0.27	-0.37	-0.17***	(-2.81)
DEMAND	-0.21	-0.21	-0.25	-0.30	-0.40	-0.20***	(-3.68)
BID_ASK	-0.21	-0.21	-0.24	-0.31	-0.38	-0.17***	(-3.11)
LN_ILLIQ	-0.22	-0.20	-0.24	-0.30	-0.40	-0.18***	(-3.52)
IV	-0.23	-0.21	-0.24	-0.28	-0.39	-0.16***	(-3.20)
IS	-0.23	-0.21	-0.20	-0.32	-0.40	-0.16***	(-2.95)
IK	-0.23	-0.19	-0.24	-0.32	-0.38	-0.16***	(-2.90)
RV_IV	-0.15	-0.21	-0.28	-0.29	-0.44	-0.29***	(-6.01)
VTS	-0.19	-0.24	-0.24	-0.30	-0.39	-0.20***	(-3.71)
dCIV	-0.23	-0.20	-0.24	-0.28	-0.39	-0.16***	(-3.53)

Table IA.8: Firm-level cross-sectional regressions of option returns with moneyness between 0.8 and 1.2

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged call option returns with moneyness between 0.8 and 1.2. Using this filter, at end of each month, we obtain 224,504 observations for both calls and puts. The average call option return is -0.29% with the median of -0.37% and the standard deviation of 3.18%. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) t-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.018***	-0.019***	-0.018***	-0.018***	-0.018***	-0.018***	-0.018***
	(-6.30)	(-6.96)	(-6.48)	(-6.03)	(-6.16)	(-6.08)	(-6.91)
BETA		0.00024					0.00023*
		(1.52)					(1.71)
SIZE			0.0011***				0.0010***
			(5.88)				(6.37)
BM				-0.00010			0.00030
				(-0.15)			(0.53)
MOM					-0.00042		-0.00043
					(-0.77)		(-0.95)
REV						0.0014	-0.000026
						(1.06)	(-0.020)
R-squared	0.005	0.010	0.015	0.009	0.012	0.010	0.031

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.018***	-0.014***	-0.019***	-0.018***	-0.016***	-0.014***
	(-6.30)	(-4.91)	(-7.14)	(-5.91)	(-4.93)	(-4.68)
IVOL		-0.070***				-0.071***
		(-3.89)				(-3.86)
MAX			0.0027**			0.0033**
			(2.22)			(2.36)
RS				-0.000065		0.000020
				(-0.57)		(0.18)
RK					-0.00010***	-0.000086***
					(-4.64)	(-3.68)
R-squared	0.005	0.014	0.010	0.007	0.009	0.024

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.018***	-0.018***	-0.018***	-0.019***	-0.019***
	(-6.30)	(-6.37)	(-6.27)	(-6.88)	(-6.91)
DEMAND		-0.018***			-0.013***
		(-6.82)			(-5.44)
BID_ASK			0.0011*		0.0024***
			(1.76)		(3.49)
LN_ILLIQ				-0.0011***	-0.0010***
				(-5.89)	(-5.44)
R-squared	0.005	0.010	0.008	0.016	0.024

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.018***	-0.013***	-0.020***	-0.018***	-0.026***	-0.014***	-0.019***	-0.022***
	(-6.30)	(-5.43)	(-7.69)	(-6.67)	(-8.71)	(-5.73)	(-7.75)	(-11.5)
IV		-0.015***						-0.013***
		(-8.95)						(-8.63)
IS			-0.024***					-0.025***
			(-8.79)					(-10.3)
IK				-0.00049				-0.0041**
				(-0.26)				(-2.35)
RV_IV					0.012***			0.0086***
					(10.7)			(6.32)
VTS						0.039***		0.0087**
						(8.33)		(2.32)
dCIV							-0.022***	-0.012***
							(-12.6)	(-7.59)
R-squared	0.005	0.029	0.012	0.007	0.014	0.016	0.015	0.056

Table IA.9: Univariate portfolios sorted on the VOV based on options with moneyness between 0.8 and 1.2

This table reports the average return of holding delta-hedged call option portfolios on Volatility of volatility (VOV), based on options with moneyness between 0.8 and 1.2. Using this filter, we obtain 224,504 observations for both calls and puts. The average call option return is -0.29% with the median of -0.37% and the standard deviation of 3.18%. At the end of each month, we rank the delta-hedged option portfolios into 5 deciles based on the VOV and then calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low " row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean. The risk-adjusted average returns are also reported in the column 3 to column 6. The risk factors including Fama and French (1993) three factors (MKT, SMB, HML), Carhart (1997) momentum factor (UMD) and Fama and French (2015) five factors (RMW, CMA) are obtained from the Kenneth R. French Data Library. The sample period is from January 1996 to April 2016. The robust Newey and West (1987) t-statistics of the high-row portfolios are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Raw return	CAPM alpha	Three-Factor alpha	Four-Factor alpha	Five-Factor alpha
Low	-0.26	-0.25	-0.26	-0.28	-0.25
2	-0.27	-0.26	-0.26	-0.28	-0.24
3	-0.26	-0.24	-0.25	-0.26	-0.24
4	-0.29	-0.28	-0.28	-0.30	-0.29
High	-0.46	-0.45	-0.45	-0.46	-0.45
High-Low	-0.19***	-0.20***	-0.20***	-0.18***	-0.20***
	(-4.52)	(-4.57)	(-4.72)	(-4.36)	(-4.46)

Table IA.10: Bivariate portfolios sorted on control variables and the VOV based on options with moneyness between 0.8 and 1.2

This table reports the average return of holding delta-hedged call option portfolios on Volatility of volatility (VOV), based on options with moneyness between 0.8 and 1.2. Using this filter, we obtain 224,504 observations for both calls and puts. The average call option return is -0.29% with the median of -0.37% and the standard deviation of 3.18%. At the end of each month, we rank the delta-hedged option portfolios into 5 deciles, based on each control variable, and then sequentially rank each decile into another 5 deciles, based on VOV. Finally, we calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low" row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. The robust Newey and West (1987) t-statistics of the high-row portfolios are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Low	2	3	4	High	High-Low	t
BETA	-0.27	-0.27	-0.25	-0.30	-0.45	-0.19***	(-5.10)
SIZE	-0.25	-0.28	-0.28	-0.31	-0.43	-0.18***	(-4.61)
BM	-0.24	-0.25	-0.25	-0.27	-0.44	-0.20***	(-4.62)
MOM	-0.26	-0.24	-0.25	-0.28	-0.44	-0.18***	(-4.44)
REV	-0.27	-0.28	-0.25	-0.29	-0.45	-0.18***	(-4.33)
IVOL	-0.29	-0.26	-0.27	-0.29	-0.43	-0.14***	(-3.30)
MAX	-0.26	-0.27	-0.26	-0.30	-0.45	-0.20***	(-5.00)
RS	-0.25	-0.26	-0.25	-0.29	-0.43	-0.18***	(-4.06)
RK	-0.26	-0.26	-0.26	-0.28	-0.42	-0.16***	(-3.56)
DEMAND	-0.25	-0.28	-0.26	-0.30	-0.45	-0.20***	(-4.78)
BID_ASK	-0.27	-0.27	-0.27	-0.29	-0.45	-0.19***	(-4.90)
LN_ILLIQ	-0.24	-0.27	-0.27	-0.31	-0.45	-0.21***	(-5.24)
IV	-0.28	-0.27	-0.28	-0.28	-0.43	-0.15***	(-4.08)
IS	-0.27	-0.26	-0.27	-0.32	-0.43	-0.15***	(-4.13)
IK	-0.28	-0.26	-0.28	-0.31	-0.42	-0.15***	(-3.64)
RV_IV	-0.23	-0.25	-0.28	-0.33	-0.46	-0.22***	(-5.65)
VTS	-0.28	-0.26	-0.29	-0.30	-0.41	-0.14***	(-4.31)
dCIV	-0.30	-0.27	-0.27	-0.27	-0.42	-0.12***	(-3.30)

Table IA.11: Firm-level cross-sectional regressions of delta-hedged call option returns held until the end of month

This table reports the average coefficients from monthly Fama and MacBeth (1973) cross-sectional regressions of delta-hedged call option returns held until the end of month. The average call option return is −0.15% with the median of −0.37% and the standard deviation of 2.19%. Volatility of volatility (VOV) is defined as the standard deviation of the ATM 30-day IV and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey and West (1987) *t*-statistics are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

Panel A: Firm-Specific Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VOV	-0.012***	-0.012***	-0.011***	-0.012***	-0.013***	-0.012***	-0.012***
	(-4.01)	(-4.15)	(-3.88)	(-3.99)	(-4.27)	(-4.00)	(-4.04)
BETA		0.00032**					0.00017
		(2.50)					(1.40)
SIZE			0.00028***				0.00023**
			(3.22)				(2.48)
BM				-0.00055			-0.00036
				(-1.48)			(-1.14)
MOM					-0.00045		-0.00049
					(-1.33)		(-1.51)
REV						-0.0013	-0.00094
						(-1.20)	(-0.87)
R-squared	0.010	0.019	0.021	0.016	0.021	0.019	0.051

Panel B: Return Distribution Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)
VOV	-0.012***	-0.0095***	-0.013***	-0.012***	-0.010***	-0.0093***
	(-4.01)	(-3.24)	(-4.58)	(-3.85)	(-3.37)	(-3.02)
IVOL		-0.043***				-0.049***
		(-3.64)				(-3.94)
MAX			-0.00033			0.0010
			(-0.28)			(0.84)
RS				-0.00032***		-0.00020**
				(-3.05)		(-2.08)
RK					-0.000071***	-0.000048***
					(-4.80)	(-3.33)
R-squared	0.010	0.026	0.020	0.017	0.018	0.048

Panel C: Limits to Arbitrage

	(1)	(2)	(3)	(4)	(5)
VOV	-0.012***	-0.012***	-0.013***	-0.012***	-0.014***
	(-4.01)	(-4.08)	(-4.50)	(-4.10)	(-4.94)
DEMAND		-0.012***			-0.014***
		(-3.87)			(-2.97)
BID_ASK			0.0026		0.0075***
			(1.63)		(4.54)
LN_ILLIQ				-0.00025***	-0.00039***
				(-2.84)	(-4.26)
R-squared	0.010	0.016	0.019	0.022	0.036

Panel D:Option-based Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VOV	-0.012***	-0.0095***	-0.013***	-0.015***	-0.017***	-0.011***	-0.013***	-0.019***
	(-4.01)	(-3.54)	(-4.50)	(-4.93)	(-5.84)	(-3.97)	(-4.56)	(-6.30)
IV		-0.0082***						-0.0080***
		(-6.97)						(-6.77)
IS			-0.014***					-0.017***
			(-5.81)					(-7.31)
IK				0.011***				0.0095***
				(5.45)				(4.32)
RV_IV					0.0073***			0.0056***
					(7.44)			(6.07)
VTS						0.022***		0.0028
						(5.77)		(0.71)
dCIV							-0.014***	-0.011***
							(-7.68)	(-5.47)
R-squared	0.010	0.043	0.022	0.017	0.024	0.028	0.026	0.093

Table IA.12: Univariate portfolios sorted on the VOV based on delta-hedged call option returns held until the end of month

This table reports the average return of holding delta-hedged call option portfolios on Volatility of volatility (VOV), based on delta-hedged call option returns held until the end of month. The average call option return is -0.15% with the median of -0.37% and the standard deviation of 2.19%. At the end of each month, we rank the delta-hedged option portfolios into 5 deciles based on the VOV and then calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low " row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean. The risk-adjusted average returns are also reported in the column 3 to column 6. The risk factors including Fama and French (1993) three factors (MKT, SMB, HML), Carhart (1997) momentum factor (UMD) and Fama and French (2015) five factors (RMW, CMA) are obtained from the Kenneth R. French Data Library. The sample period is from January 1996 to April 2016. The robust Newey and West (1987) t-statistics of the high-row portfolios are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Raw return	CAPM alpha	Three-Factor alpha	Four-Factor alpha	Five-Factor alpha
Low	-0.096	-0.083	-0.083	-0.11	-0.080
2	-0.15	-0.13	-0.14	-0.16	-0.12
3	-0.15	-0.14	-0.14	-0.16	-0.15
4	-0.19	-0.17	-0.17	-0.19	-0.18
High	-0.24	-0.23	-0.23	-0.25	-0.24
High-Low	-0.15***	-0.15***	-0.15***	-0.14***	-0.16***
	(-4.32)	(-4.30)	(-4.47)	(-4.00)	(-4.50)

Table IA.13: Bivariate portfolios sorted on control variables and the VOV based on delta-hedged call option returns held until the end of month

This table reports the average return of holding delta-hedged call option portfolios on Volatility of volatility (VOV), based on delta-hedged call option returns held until the end of month. The average call option return is -0.15% with the median of -0.37% and the standard deviation of 2.19%. At the end of each month, we rank the delta-hedged option portfolios into 5 deciles, based on each control variable, and then sequentially rank each decile into another 5 deciles, based on VOV. Finally, we calculate the equal-weighted monthly returns of those 5 portfolios. This table also reports the difference in the average returns of the low and the high VOV decile portfolios in the "High-Low" row. VOV is defined as the standard deviation of the ATM 30-day IV scaled by its mean and the details of control variable construction are provided in Appendix A.2. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. The robust Newey and West (1987) t-statistics of the high-row portfolios are reported in parentheses. *, ** and *** indicates significance at the 10, 5 and 1% level.

	Low	2	3	4	High	High-Low	t
BETA	-0.10	-0.13	-0.17	-0.18	-0.26	-0.16***	(-5.07)
SIZE	-0.13	-0.13	-0.16	-0.18	-0.25	-0.12***	(-3.63)
BM	-0.08	-0.14	-0.15	-0.16	-0.25	-0.17***	(-5.24)
MOM	-0.10	-0.13	-0.13	-0.17	-0.24	-0.15***	(-4.89)
REV	-0.09	-0.15	-0.15	-0.18	-0.25	-0.17***	(-4.94)
IVOL	-0.11	-0.16	-0.15	-0.18	-0.24	-0.13***	(-4.39)
MAX	-0.10	-0.15	-0.15	-0.19	-0.26	-0.16***	(-5.21)
RS	-0.08	-0.14	-0.14	-0.17	-0.24	-0.16***	(-4.41)
RK	-0.09	-0.15	-0.13	-0.17	-0.24	-0.15***	(-4.29)
DEMAND	-0.10	-0.15	-0.16	-0.17	-0.27	-0.17***	(-5.57)
BID_ASK	-0.11	-0.15	-0.15	-0.18	-0.25	-0.15***	(-4.07)
LN_ILLIQ	-0.12	-0.14	-0.15	-0.19	-0.25	-0.13***	(-3.98)
IV	-0.12	-0.14	-0.16	-0.18	-0.24	-0.12***	(-3.88)
IS	-0.11	-0.14	-0.15	-0.20	-0.25	-0.13***	(-4.03)
IK	-0.10	-0.14	-0.15	-0.18	-0.27	-0.17***	(-5.17)
RV_IV	-0.08	-0.13	-0.17	-0.18	-0.28	-0.20***	(-6.55)
VTS	-0.09	-0.15	-0.16	-0.20	-0.23	-0.14***	(-4.88)
dCIV	-0.13	-0.13	-0.13	-0.19	-0.25	-0.12***	(-4.71)