Volatility Uncertainty and the Cross-Section of Option Returns*

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Abstract

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Abstract

This paper studies the relation between the uncertainty of volatility, measured as the volatility of volatility, and future *delta-hedged* equity option returns. We find that *delta-hedged* option returns consistently decrease in uncertainty of volatility. Our results hold for different measures of volatility such as implied volatility, EGARCH volatility from daily returns, and realized volatility from high-frequency data. The results are robust to firm characteristics, stock and option liquidity, volatility characteristics, jump risks, and are not explained by common risk factors. Our findings suggest that option dealers charge a higher premium for single-name options with high uncertainty of volatility, because these stock options are more difficult to hedge.

Keywords: Delta-hedged option returns; volatility estimates; uncertainty of volatility

JEL Classification: G12; G1

1. Introduction

An enormous body of work has documented that volatility in asset returns is time varying[1]. Modeling the dynamics of volatility has important implications for explaining the phenomena in financial markets, such as volatility smile and skew, and for pricing derivatives more accurately, compared with models with constant volatility. While there is a consensus that stochastic volatility is important for financial econometrics and asset pricing[2], an equally important but less examined aspect is how the uncertainty in time-varying volatility affects cross sectional asset returns.

In this paper, we study whether uncertainty of volatility can predict future cross-sectional equity option returns. Previous studies point out that option arbitrageurs in imperfect markets face "model risk", especially when they write options (e.g., Figlewski (1989, 2017) and Figlewski and Green (1999)). Figlewski and Green (1999) show that an important source of model risk is that not all of the input parameters, especially the volatility parameter, are observable. Even if one has a correctly specified model, using it requires knowledge of the volatility of the underlying asset over the lifetime of the contract. Option arbitrageurs face higher model risk when the volatility parameter is more uncertain. In particular, when it comes to the risk management practice of delta-hedging, proper hedging requires that the pricing model is correct, and also requires the right volatility input. Thus, pricing and hedging errors due to inaccurate volatility estimates create sizable risk exposure for option writers. To mitigate the risk associated with volatility uncertainty, risk-averse option writers charge a higher option implied volatility to compensate for model risk. Thus, increased uncertainty on the underlying stock volatility translates into option sellers charging a higher option premium, leading to lower option returns for buyers.

To empirically test our hypothesis, we use the delta-hedged option portfolios so that portfolio returns are primarily affected by volatility changes and are insensitive to stock price

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[1] The literature includes ARCH/GARCH models of Engle (1982) and Bollerslev (1986), and the stochastic volatility model of Heston (1993). Recent studies use high-frequency data to directly estimate the stochastic volatility process (See Barndorff- Nielsen and Shephard (2002), Bollerslev and Zhou (2002), and Andersen, Bollerslev, Diebold, and Labys (2003)).

[2] Representative work of empirical studies on the pricing of volatility in the stock market include Ang, Hodrick, Xing, and Zhang (2006), Barndorff-Nielsen and Veraart (2013). More recently, Campbell, Giglio, Polk, and Turley (2017) introduce an intertemporal CAPM with stochastic volatility. McQuade (2016) shows that introducing stochastic volatility in the firm productivity process sheds new light on the value premium, financial stress, and momentum puzzles.

movements. We formally test this hypothesis by studying the predictability of volatility uncertainty on future delta-hedged equity option returns. We measure volatility uncertainty as the volatility-of-volatility (VOV) using three estimates of volatility: (1) implied volatility from 30 day to maturity options, (2) volatility estimated from an EGARCH (1,1) model using rolling 252 days, and (3) intraday realized volatility from 5-minute returns. Next, we compute the standard deviation of the percentage change of the daily volatility level over the previous month.[3]

We find that the three VOV measures predict future option returns. Fama-French regressions report a negative and significant relation between each VOV estimate and monthly delta-hedged option returns. Firms with higher (lower) VOV in the previous month have significantly lower (higher) delta-hedged option returns in the next month. The negative relation holds for call and put options with coefficients and significance levels similar in both cases. Multivariate regressions reveal that the coefficients of the three VOV measures are negative and statistically significant.

Our results cannot be explained by volatility-related variables such as idiosyncratic volatility in Cao and Han (2013), volatility deviation in Goyal and Saretto (2009), or the slope of the volatility term structure in Vasquez (2017). The results are robust after controlling for the volatility risk premium, implied jump risk measures (Bolleslev and Todorov (2011)), implied skewness (Bakshi, Kapadia, and Madan (2003)), volatility spread (Yan (2011)), stock and option liquidity, and option demand pressure. The VOV effect cannot be explained by alternative firm-level information uncertainty measures such as the analyst coverage and dispersion measure, the information asymmetry measure proxied by stock PIN, or firm characteristics that predict option returns (Cao, Han, Tong, and Zhan (2017)).

We also explore the relation between option returns and higher order moments of volatility such as skewness and kurtosis. We find that skewness-of-volatility and kurtosis-of-volatility significantly predict future option returns. After controlling for skewness- and kurtosis-of-volatility, the three VOV measures are still statistically significant, suggesting that VOV carries information not contained in skewness- and kurtosis-of-volatility.

[3] This definition of VOV is motivated by the definition of VVIX index provided by CBOE, which is a volatility of volatility measure that represents the expected volatility of the 30-day forward price of the VIX.

To investigate the economic magnitude of the predictability, we form quintile portfolios of delta-neutral covered call writing strategy sorted on VOV. To remove the exposure to stock price movements, we perform daily rebalancing of the stock position. At the end of each month, we sort all stocks with qualified options by their VOV and form quintile portfolios of short delta-neutral covered calls. We find that the average returns decrease monotonically from quintile 1 to quintile 5. The return spread between the top and bottom quintiles is statistically significant for the three VOV measures ranging from 0.52% to 1.04% per month. The results are robust to different weighting schemes.

To comprehensively capture the information contained in the three different VOV estimates, we create a combined VOV measure computed as the average of the ranking percentile of the individual VOV measures. The combined VOV return spreads and its t-statistics are higher than any of the ones generated by the individual VOV measures. The economic and statistical significance of the long-short returns remains unchanged even after controlling for common risk factors in the stock and option markets.

To further understand the sources of the VOV predictability, we explore several potential explanations. First, we examine to which extent the VOV effect is related to news arrival (e.g., earning announcements) and only reflects biased expectations by option arbitrageurs. We find no evidence that the return spread comes from the short window around earnings announcements, suggesting that the VOV effect is less likely to be explained by the hypothesis that options with high VOV are more overpriced and such mispricing are corrected once upon the firm-specific information is released.

Second, we decompose VOV into a positive (VOV+) and a negative component (VOV-). VOV+ is defined as the volatility of the positive percentage change of volatility and VOV- is the volatility of the negative percentage change of volatility. For implied VOV, univariate regressions show that VOV+ has a large negative impact on future option returns while the impact of VOV- is not significant. Multivariate regressions confirm the negative effect of VOV+ while the effect of VOV- becomes significantly positive. These results suggest that option writers dislike increases in implied volatility, or VOV+, much more than they dislike decreases in implied volatility, VOV-. The results for the realized VOV measures are different. Both realized VOV+ and VOV- are significantly negative related with future option returns. These results suggest that option market makers and proprietary traders might be using realized volatility for market making and arbitrage. Both an increase and a decrease of realized volatility increase the hedging costs and lead to an increment in the option price.

Lastly, we explore if a common systematic factor explains the predictability of VOV. We decompose VOV into a systematic and idiosyncratic component. We find that most of the predictability comes from volatility-of-idiosyncratic-volatility. The results are robust to two alternative methods of systematic/idiosyncratic decomposition of VOV. We conclude that the VOV effect cannot be reconciled with classic risk-based theories such as the arbitrage pricing model or the ICAPM model. Our results seem more consistent with the idea that hedging options with high volatility-of-idiosyncratic-volatility is more difficult and costly, which leads to higher option prices and future lower returns.

Our paper contributes to several strands of literature. First, our paper is among the first to study the cross-sectional relation between VOV and future delta-hedged equity option returns.[4] Independent work by Ruan (2018) performs a similar study. However, there are several differences between our study and that of Ruan (2018). First, we study monthly delta-hedged option returns where the delta hedged position is rebalanced daily instead of monthly. Dynamic delta-hedging makes the position sensitive only to volatility changes and insensitive to stock price movements. Hence, daily delta-hedging is superior to monthly delta hedging to achieve a delta-neutral position. Second, we study 3 measures of volatility (implied, EGARCH, and intra-day volatilities) instead of one. Third, to further understand the relation between option returns and VOV, we decompose VOV in two different ways: systematic and idiosyncratic, and positive and negative VOV.

Second, our paper explores the impact of volatility uncertainty on the equity options market. Other papers have explored the impact of VOV in other markets such as the stock market (Baltussen, Van Bekkum, and Van Der Grient (2017)), and the hedge-fund market (Agarwal, Arisoy, and Naik (2017)). The impact of the aggregate VOV, as a systematic risk factor, on the stock market is also investigated by Chen, Chordia, Chung, and Lin (2017), and

[4] There is a growing literature on the cross-sectional equity option return predictability. See e.g., the deviation between implied volatility and realized volatility (Goyal and Sarreto (2009)), idiosyncratic volatility (Cao and Han (2013)), stock skewness (Bali and Murray (2013), Boyer and Vorkink (2014)), volatility term structure (Vasquez (2017)), option illiquidity premium (Christoffersen, Goyenko, Jacobs, and Karoui (2018)), option market order-flow imbalance (Muravyev (2016)), many firm characteristics (Cao et al. (2017)), firm leverage and credit risk (Vasquez and Xiao (2017)), and CDS trading of underlying stock (Cao, Jin, Pearson, and Tang (2017)). Different from the previous literature, our paper uses distributional characteristics of volatility movements to predict delta-hedged option return.

Hollstein and Prokopczuk (2017). Huang, Schlag, Shaliastovich, and Thimme (2018) document the impact of systematic VOV on index options and VIX options. We contribute to this literature by focusing on the effect of VOV on future delta-hedged equity option returns.[5]

The rest of the paper is organized as follows. Section 2 describes the data and the volatility uncertainty measures. Section 3 reports the main empirical results and various robustness checks. Section 4 presents further discussions and Section 5 concludes.

2. Data and Variables

2.1. Data and sample coverage

Option data on individual stocks are from the OptionMetrics Ivy DB database. The database contains information on the entire U.S. equity option market, including daily closing bid and ask quotes, open interest, volume, implied volatility, and Greeks such as delta, gamma and vega from January 1996 to April 2016. Implied volatility and Greeks are calculated by OptionMetrics using the binomial tree from Cox, Ross, and Rubinstein (1979). We obtain stock returns, prices, and trading volume from the Center for Research on Security Prices (CRSP). The annual accounting data are obtained from Compustat. We obtain the quarterly institutional holding data from Thomson Reuters (13F) and the analyst coverage and forecast data from I/B/E/S. The high frequency data of stock prices are from the TAQ database.

We apply several filters to select the options in our sample. First, to avoid illiquid options, we exclude options if the trading volume is zero, or if the bid quote is zero, or if the bid quote is smaller than the ask quote, or if the average of the bid and ask price is lower than 0.125 dollars. Second, we discard options whose underlying stock pays a dividend during the remaining life of the option to remove the effect of early exercise premium in American options. Therefore, options in our sample are very close to European style options. Third, we exclude all options that violate no-arbitrage restrictions. Fourth, we only keep options with moneyness between 0.8 and 1.2. At the end of each month and for each stock with options, we select one call and one put option that are the closest to being at-the-money with the shortest maturity among those options

[5] Since the delta-hedged option return is essentially insensitive to the movement of stock price, the predictability investigated in our study is not inherited from the predictability of volatility of volatility on stock return documented in Baltussen et al. (2017).

with more than one month to maturity. We drop options whose maturity is different from the majority of options.[6]

Our final sample contains 327,016 option-month observations for calls and 305,710 option-month observations for puts. Table 1 reports the summary statistics of the call and put options in our sample. The average moneyness of the call options and the put options are both close to 1 with a standard deviation of 5%. The time to maturity ranges from 47 to 50 days. The vega does not have much variation in our sample, ranging from 0.13 to 0.15 with a standard deviation of 0.01%. The dataset covers 8,174 unique stocks over the entire sample and 1,627 stocks per month on average.

2.2. Delta-hedged option returns

Given that an option is a derivative of a stock, option returns are highly sensitive to stock returns. We follow the literature and study the gain of delta-hedged options, such that the portfolio gain is not sensitive to the movement of the underlying stock. In the Black-Scholes model, the expected gain of a delta-hedged option portfolio is zero because the option position can be completely hedged by the position on the underlying stock. Empirical studies find that the average gain of the delta-hedged option portfolios is negative for both indexes and individual stocks (Bakshi and Kapadia (2003), Carr and Wu (2009) and Cao and Han (2013)).

We follow Bakshi and Kapadia (2003) and Cao and Han (2013) to calculate the delta-hedged gain. A delta-hedged call option portfolio consists of an option position, hedged by a short position in the underlying stock, where the position of the stock is equal to the delta of the option. The delta-hedged gain for a call option portfolio from time t to time t+ τ in excess of the risk-free rate earned by the portfolio is

$$\widehat{\prod}(t, t+\tau) = C_{t+\tau} - C_t - \int_t^{t+\tau} \Delta_u \, dS_u - \int_t^{t+\tau} r_u \, (C_u - \Delta_u S_u) du, \qquad (1)$$

where C_t is the call option price, $\Delta_t = \partial C_t / \partial S_t$ is the call option delta, and r_t is the risk-free rate. In the empirical analysis, we use a discrete version of equation (1). In discrete time, the call option is hedged N times over a period $[t, t+\tau]$ in which the delta position is updated at each t_n.

[6] Relaxing any of the filters on the options or on the underlying stocks does not affect the main result of this paper.

The discrete version of the delta-hedged call option gain in excess of risk free rate earned by the portfolio is

$$\prod(t, t+\tau) = C_{t+\tau} - C_t - \sum_{n=0}^{N-1} \Delta_{C,t_n} [S(t_{n+1}) - S(t_n)] - \sum_{n=0}^{N-1} \frac{\alpha_n r_{t_n}}{365} \left[C(t_n) - \Delta_{C,t_n} S(t_n)\right], (2)$$

where Δ_{C,t_n} is the delta of the call option on date t_n, r_{t_n} is the annualized risk-free rate on date t_n, and α_n is the number of calendar days between t_n and t_{n+1}. The definition of the delta-hedged put option gain replaces the call price and call delta by the put price and put delta in equation (2). To make the option return comparable across stocks, we follow Cao and Han (2013) who scale the delta-hedged gain as $(\Delta_t * S_t - C_t)$ for calls and as $(P_t - \Delta_t * S_t)$ for puts, which is the negative value of the initial investment.[7]

Table 1 shows that the average delta-hedged returns are negative for both call and put options, consistent with previous findings in Bakshi and Kapadia (2003) and Cao and Han (2013). For example, the average delta-hedged returns for call options until month-end and until maturity are -0.82% and -1.11%, respectively. The average returns for delta-hedged put options are of similar magnitude.

[Insert Table 1 about here]

2.3. Volatility-of-volatility (VOV) measures

We calculate monthly volatility-of-volatility (VOV) based on three measures of daily volatility estimates.

The first measure of daily volatility is extracted from the volatility surface provided by OptionMetrics. The advantage of using the volatility surface is that daily implied volatilities have constant maturity and delta. We work with implied volatilities of call options that have a delta of 0.5 and 30 days to maturity. Then we use the daily implied volatilities within a given month to calculate the monthly VOV, which is described below.[8]

[7] We obtain similar results when we scale by the initial price of the underlying stock or by the initial price of the option.

[8] For each stock and each month, we require at least 15 observations of daily implied volatility to calculate VOV.

The second measure of daily volatility is estimated using the following EGARCH (1,1) model with daily stock returns[9]:

$$r_t = \sigma_t z_t; \quad ln\sigma_t^2 = \omega + \alpha\, r_{t-1}^2 + \beta\, ln\sigma_{t-1}^2 + \gamma[|z_{t-1}| - \left(\frac{2}{\pi}\right)^{\frac{1}{2}}]$$

where r_t is the stock return, σ_t is the conditional volatility, and z_t is the innovation term. For each stock in a given month, we apply the EGARCH (1, 1) model to a rolling window of the past 12-month daily stock returns (including the current month).[10] It generates a series of time-varying volatility levels for each day in the estimation window. The maximum number of iterations is 500 for the maximum likelihood estimation and over 96% of the EGARCH regressions in our sample successfully converge.

The third measure of daily volatility is computed from the historical tick-by-tick quote data from TAQ database. We record prices every five minutes starting at 9:30 EST and construct five-minute log-returns for a total of 78 daily returns. We use the last recorded price within each five-minute period to calculate the log return. To ensure sufficient liquidity, we require that a stock has at least 80 daily transactions to construct a daily measure of realized volatility.

For the three measures of volatility, we calculate the percentage change in daily volatility as $\frac{\Delta\sigma}{\sigma} = \frac{\sigma_t - \sigma_{t-1}}{\sigma_{t-1}}$, where σ_t is the volatility on day t. The monthly VOV measure is defined as the standard deviation of the daily percentage change in volatility within each month. This definition of VOV is different from the measure in Baltussen et al. (2017), which is defined as the standard deviation of implied volatility scaled by the average implied volatility level within each month. The correlation between the two VOV definitions is around 0.7. The main reason to define our VOV measure based on the "return of volatility" is to be in line with the *VVIX index* from CBOE. *VVIX* is defined on the CBOE website as the implied volatility of VIX futures returns. If we consider volatility as an asset, similar to a stock, then the volatility of this asset is defined based on its return. Using the VOV measure defined in Baltussen et al. (2017) does not change our conclusions as reported in the Supplementary Appendix.

[9] GARCH models have been widely used to model the conditional volatility of returns. Pagan and Schwert (1990) fit a number of different models to monthly U.S. stock returns and find that Nelson (1991)'s EGARCH model is the best in overall performance. EGARCH models are able to capture the asymmetric effects of volatility, and they do not require restricting parameter values to avoid negative variance as do other ARCH and GARCH models.

[10] A typical EGARCH regression has about 252 daily return observations. We require at least 200 daily returns. In robustness checks, we estimate alternative EGARH (p, q) models, for p and q up to 3.

Figure 1 shows the distributions of the three daily volatility levels (Panels A, B, and C) and of the percentage change in volatility (Panels D, E, and F). The distribution of all three daily volatility level measures resembles the log normal distribution. In contrast, the distribution of the daily percentage change in volatility exhibits a symmetric bell shape. This renders feasibility to apply standard statistical inferences such as the physical measure of standard deviation in our analyses to estimate the volatility-of-volatility.

[Insert Figure 1 about here]

[Insert Table 2 about here]

Table 2 reports summary statistics for the three volatility measures in Panels A, B, and C. We report their higher moments: volatility-of-volatility, skewness-of-volatility, and kurtosis-of-volatility. The mean of the three volatility measures is very similar: 0.48 for IMPLIED-VOV, 0.47 for EGARCH-VOV, and 0.45 for INTRADAY-VOV. The level of the volatility of the percentage change in volatility (VOV), however, differs across the three measures. INTRADAY-VOV has the highest mean 0.39 and EGARCH-VOV has the lowest mean of 0.19, suggesting that the volatility from high-frequency returns is more volatile than the volatility from low frequency (daily) returns. The skewness of the percentage change in volatility (SOV) is positive for the three volatility measures.

Panel D in Table 2 reports the cross-sectional correlations among the VOV measures. The correlation among the VOV measures is between 7% and 12%. The low correlation among the VOV measures suggests that the three measures may contain distinct information. Option implied volatility is a forward looking estimate of the volatility in the next 30 days. Since option prices are usually quoted in implied volatility, IMPLIED-VOV reflects the standard deviation of historical option prices. Option trader's expectations might be affected more by the IMPLIED-VOV than by the other two realized VOV measures. EGARCH measure uses daily stock returns to estimate daily conditional volatility and the intraday VOV measure uses high-frequency data which contain information that the other two measures do not have. In the equity option market, option traders make investment decisions relying on different information sets, e.g. from historical stock return data, historical option price data or high frequency data. Hence, the three VOV measures might all have information content in predicting future option returns.

3. Empirical Results

In this section, we present empirical evidence from Fama-Macbeth cross-sectional regressions and portfolio sorts on the predictive power of the three VOV measures on option returns. We first show regression results of daily-rebalanced delta-hedged option returns on VOV measures. Then we report robustness check results. Lastly, we implement cross-sectional long-short portfolios based on the return of a delta-neutral call writing strategy.

3.1. Delta-hedged option gains and VOV: Cross-sectional regressions

We first study the predictive power of VOV measures on future delta-hedged option gains in the cross section using monthly Fama-MacBeth regressions. The dependent variable in month *t* is the delta-hedged option gain until month end scaled by the initial investment of the option portfolio: $\prod(t, t+\tau)/(\Delta_t * S_t - C_t)$ for calls and $\prod(t, t+\tau)/(P_t - \Delta_t * S_t)$ for puts. To avoid the impact of outliers in the regressions, every month we winsorize all explanatory variables at the 0.5% and 99.5% levels. We conduct tests on the time-series averages of the slope coefficients from the regressions. To account for potential autocorrelation and heteroskedasticity in the coefficients, we compute Newey and West (1987) adjusted t-statistics based on the time-series of the estimated coefficients.

Table 3 Panel A reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns on VOV measures for call and put options. The coefficients of the three VOV measures are significantly negative for call and put options. These results confirm the theoretical results in Figlewski and Green (1999) and support the argument that option writers charge a higher premium when facing greater uncertainty in the underlying stock volatility. The average coefficients for the 3 VOV measures is negative and with a significance above 6. We conduct a joint Fama-MacBeth regression with the three VOV measures and the 3 coefficients remain statistically significant. Moreover, the adjusted R^2 of the joint regression is higher than that of any of the univariate regressions, suggesting that the three VOV measures together explain a larger portion of cross sectional variation in option returns. The findings are similar for call and put options. The results remain unchanged when using the alternative VOV definition from Baltussen et al. (2017) as reported in the Appendix, Table A1.

[Insert Table 3 about here]

We also check the robustness of our results to different definitions of option returns. Table 3, Panel B reports joint regression of the three VOV measures on four definitions of option returns: i) delta-hedged gain till month-end scaled by stock price, ii) delta-hedged gain till month-end scaled by stock price, iii) delta-hedged gain till maturity scaled by initial investment, and iv) delta-hedged gain till week end scaled by initial investment. The initial investment is (Δ*S - C) for calls and (P - Δ*S) for puts. The results are robust to the holding period of the return as well as to the variable used to scale the delta-hedged gain. We conclude that the three VOV measures predict weekly and monthly option returns.

3.2. Fama-Macbeth regressions with control variables

In this subsection, we study whether the effect of VOV can be explained by different sets of control variables. Each month, we conduct cross-sectional regressions of delta-hedged option returns on VOV measures and one or more control variables. For the remaining tests, we focus on call options. The results for put options are similar to those for call options and are available upon request.

3.2.1. Control for volatility related measures

The negative VOV effect might be explained by several volatility-related measures that predict future delta-hedged option returns. Specifically, higher levels of VOV might be the result of market frictions, investors' overreaction or inaccurate estimation of volatility. In Panel A of Table 4 we control for three volatility-related variables. This first variable is IVOL, the annualized stock return idiosyncratic volatility defined in Ang et al. (2006) and Cao and Han (2013). Cao and Han (2013) find that delta-hedged equity option returns decreases with idiosyncratic volatility of the underlying stock, which is consistent with market imperfections and constrained financial intermediaries. Since options with high idiosyncratic volatility or high VOV are both characterized as difficult to hedge, it is possible that the information content of VOV is subsumed in idiosyncratic volatility. The second variable is VOL_deviation defined as the log difference between the realized volatility and the Black-Scholes implied volatility for at-the-money options at the end of last month. The realized volatility is the annualized standard deviation of stock returns estimated from daily data over the previous month. Goyal and Saretto (2009) conclude that the significant negative relation of VOL_deviation and delta-hedged option returns is consistent with mean reversion of volatility and with investors' overreaction. The third variable is the VTS slope, defined as the difference between the long-term and short-term volatility in Vasquez (2017). Vasquez (2017) finds that VTS slope is a strong predictor variable of the future straddle returns of individual stocks because of investor overreaction and underreaction. When option traders overreact to certain information, the time series of volatility movement becomes more volatile and characterizes with high VOV. When the overreaction is corrected, implied volatility decreases and option return becomes lower in the next period.

Table 4, Panel A shows that the three VOV variables remain negative and significant after controlling for volatility measures that predict option returns. Overall, the result suggests that our documented impact of VOV on the cross-sectional delta-hedged option returns cannot be explained by volatility-related mispricing or frictions of financial intermediaries documented in the previous literature.

[Insert Table 4 about here]

3.2.2. Control for variance risk premium

Another possibility is that our documented effects come from the relation between VOV and variance risk premium. Previous studies (e.g., Bakshi and Kapadia (2003); Bakshi et al. (2003)) show that delta-hedged option gains are related to the variance risk premium. Bollerslev, Tauchen, and Zhou (2009) show, in an extended long-run risk model, that variance risk premium at the index level is proportional to the time varying volatility-of-volatility. Consequently, VOV and future delta-hedged option returns are potentially linked through variance risk premium. While the source and significance of individual stock variance risk premium are still not well understood, they can be empirically estimated (see e.g., Carr and Wu (2009), and Han and Zhou (2015)) and theoretically related to the expected delta-hedged option gains under a stochastic volatility model (e.g., Bakshi and Kapadia (2003)). We examine whether our results can be explained by the relation between individual variance risk premium and VOV measures.

We compute the variance risk premium as the difference between realized and implied volatilities following Jiang and Tian (2005), and Bollerslev et al. (2009). The risk-neutral expected stock variance premium is extracted from a cross-section of equity options on the last trading day of each month and the realized counterpart is proxied by realized variance computed from high-frequency returns over the given month.

Table 4 Panel B reports the Fama-MacBeth regressions when controlling for the one-month individual stock variance risk premium (VRP). The individual stock variance risk premium in all regressions has a significantly positive coefficient consistent with the findings in previous literature. More importantly, after controlling for VRP, the coefficients for the three VOV measures remain negative and significant at the 1% level. Therefore, individual stock variance risk premium does not explain the significant empirical relation between delta-hedged option returns and VOV.

3.2.3. Control for jump risk

As argued by Figlewski and Green (1999), option dealers may charge a premium for jump risk when they write options. The negative VOV effect might potentially reflect a compensation for jump risk. Firms with higher uncertainty in volatility may experience sudden stock price jumps, either positive or negative. To address the concern that the effect of VOV is explained by the jump risk of individual stocks, we consider three sets of jump measures. The first set contains the model-free left and right jump tail measures calculated from option prices according to Bolleslev and Todorov (2011). The second jump risk variable is risk-neutral skewness given that jump risk manifests itself in implied skewness when it deviates from zero. The risk-neutral skewness of stock returns is inferred from a portfolio of options across different strike prices following Bakshi et al. (2003). Since the calculation of implied skewness requires at least three out-of-the-money call options and three out-of-the-money put options the sample is reduced to about one third of the original sample. The third variable is the volatility spread defined as the spread of implied volatility between at-the-money call and put options according to Bali and Hovakimian (2009) and Yan (2011).

Panel C of Table 4 reports the Fama-MacBeth regression results when controlling for jump risk. The coefficients of the left and right jump tail measures are both statistically negative, indicating that higher jump risk predicts lower delta-hedged option returns, irrespective of the direction of the jump. The coefficients of implied skewness and volatility spread are also significant in all regressions. Overall, the coefficients of the VOV measures remain economically large and significant.

3.2.4. Control for liquidity and option demand pressure

Liquidity and demand pressure have been shown to impact option prices. Christoffersen et al. (2018) document a significant illiquidity premia in equity option markets. Bollen and Whaley (2004) and Garleanu, Pedersen, and Poteshman (2009) argue that demand pressure plays an important role when pricing options. Options with High VOV could be those with high liquidity or high demand pressure and hence yield lower returns. For illiquidity we use two variables: stock illiquidity proxied with the Amihud measure and option illiquidity proxied with the option bid-ask spread. Amihud is calculated as the average of the daily Amihud (2002) illiquidity measure over the previous month. Option bid-ask spread is the ratio of the difference between the bid and ask quotes of option to the midpoint of the bid and ask quotes at the end of previous month. We consider two option demand pressure variables: option demand pressure and Ln (total size of all calls). Option demand pressure is calculated as (Option open interest / stock volume) $\times 10^3$. Option open interest is the total number of option contracts that are open at the end of the previous month. Stock volume is the stock trading volume over the previous month. Ln (total size of all calls) is the logarithm of the total market value of the open interest of all call options.[11]

Table 5 reports the Fama-Macbeth regression results of the delta-hedged option returns on VOV measures when controlling for liquidity and demand pressure. We confirm the results in Christoffersen et al. (2018) that the higher the option illiquidity, the lower the expected option returns. The stock illiquidity measure and the two option demand pressure measures are also statistically significant in all regressions. More important, the three VOV variables remain negative and significant even after controlling for illiquidity and demand pressure.

[Insert Table 5 about here]

3.2.5. Control for stock information uncertainty and asymmetry

[11] Our results do not change materially if we use the option-trading volume of the previous month rather than option open interest or if we scale by the stock's total shares outstanding.

VOV measures the uncertainty of firm-level volatility, which could be potentially correlated with other uncertainty measures about the firm fundamentals or information asymmetry. We control for two other types of information uncertainty and one type of information asymmetry that might affect delta-hedged option returns. Previous literature finds that information risk affects expected stock returns. Diether, Malloy, and Scherbina (2002) and Zhang (2006) find that lower analyst coverage is associated with higher expected stock returns. Moreover, a smaller degree of consensus among analysts, or more dispersion in the expected earnings of a firm, negatively predicts stock returns. Easley, Hvidkjaer, and O'hara (2002) find that the probability of information-based trading (PIN) affects asset prices. Although there are no previous findings on information uncertainty, information asymmetry, and delta-hedged option return, we consider analyst coverage, analyst dispersion, and PIN as control variables for VOV.

Table 6 shows the results of Fama-Macbeth cross-sectional regressions when controlling for information uncertainty and information asymmetry. Consistent with the channel of information risk, the result suggests that the lower the analysis coverage and the higher the dispersion, the lower are the future delta-hedged option returns. The negative VOV effect remains significant after controlling for the information uncertainty and asymmetry measures. The results indicate that the effect of VOV is robust after controlling for measures of uncertainty.

[Insert Table 6 about here]

3.2.6. Control for firm characteristics

Cao et al. (2017) find that several stock characteristics and firm fundamentals predict the cross-section of delta-hedged equity option returns. We control for the variables with significant predictive power in their paper: size, reversal, momentum, cash-to-asset ratio, new issues, and profitability. Size is measured as the natural logarithm of the market value of the firm's equity (e.g., Banz (1981) and Fama and French (1992)). Reversal is the lagged one-month return as in Jegadeesh (1990). Momentum is the cumulative return on the stock over the 11 months ending at the beginning of the previous month as in Jegadeesh and Titman (1993). The cash-to-assets ratio is defined as the value of corporate cash holdings over the value of the firm’s total assets as in Palazzo (2012). New issues, as in Pontiff and Woodgate (2008), is measured as the change in shares outstanding from 11 months ago. Profitability, as in Fama and French (2006), is calculated as earnings divided by book equity, where earnings is defined as income before extraordinary items.

Table 7, Panel A reports the Fama-Macbeth regression results when controlling for firm characteristics. We find that all firm characteristics are highly significant in the Fama-Macbeth cross-sectional regressions. The strongest predictor among these characteristics is profitability. After controlling for firm characteristics, the three VOV measures remain significantly negative in all regressions with t-statistics ranging from -3.21 to -6.98, suggesting that the negative VOV effect cannot be explained by these firm characteristics.

[Insert Table 7 about here]

3.2.7 Higher-order moments of volatility change

Up to now, we have examined the impact of VOV on the cross-section of equity option returns. While VOV describes the dispersion of volatility change, higher moments of volatility change may also be considered as important to option market participants. In this subsection, we expand our analysis to two additional moments of volatility change: skewness and kurtosis. For each of the three volatility measures, we calculate the skewness and kurtosis of percentage change in volatility for each stock each month. Using Fama-Macbeth regressions, we examine the impact of volatility, skewness, and kurtosis of volatility on next month delta-hedged call and put options returns. By doing so, we can further ensure the robustness of VOV and expand our study to higher moments of volatility change.

Table 8 reports the average coefficients, t-statistics, and adjusted R-squared, with each column reporting one method to estimate volatility. The relation between VOV and option returns is negative and significant for the three measures. The coefficients of skewness and kurtosis of change in volatility are significant in most regressions, suggesting that these higher moments of volatility also contain information that predicts future option returns. However, the signs are not consistent across the three measures. Overall, we find that higher order moments of volatility such as skewness and kurtosis cannot explain the option return predictability of VOV.[12]

[12] Appendix Table A2 shows the results of alternative measures of those high-order moments. The alternative volatility of volatility is defined as the standard deviation of volatility scaled by the average of volatility in each month. The alternative skewness- and kurtosis-of-volatility are defined as skewness and kurtosis of daily volatility level in each month.

[Insert Table 8]

To summarize, we find that the VOV measures are significant determinants of the cross-sectional delta-hedged option returns. The significant negative relation is robust after controlling for liquidity, demand pressure, volatility-related mispricing, variance and jump risk, alternative uncertainty variables, stock characteristics, and higher moments of volatility.

3.3. Portfolio analysis

The patterns of VOV and future delta-hedged option returns found in the Fama-Macbeth regressions suggest a set of profitable trading strategies in the equity option market. In this subsection, we explore portfolio sorts for equity options using VOV measures. We focus on the delta-neutral call writing on individual stocks, which consists of a short position in an at-the-money call option and a long position of delta-shares of the underlying stocks.[13] The position is held for a month with daily rebalancing of the delta hedging. For each stock, we compound the daily return of the rebalanced delta-hedged call option position to obtain the monthly return. Table 9, Panel A shows that the average return is positive. This is consistent with the negative average delta-hedged option gain, which is long the option and shorts the underlying stock, opposite to delta-neutral call writing.

[Insert Table 9 about here]

3.3.1. Single portfolio sorts on VOV measures

Every month we sort all optionable stocks into five quintiles.[14] We rank stocks based on four VOV measures: IMPLIED-VOV, EGARCH-VOV, INTRADAY-VOV, and Combined-VOV. The combined VOV measure is the average of the ranking percentile of the three individual VOV measures. This methodology is used by Stambaugh, Yu, and Yuan (2015) and Cao and Han (2016) when combining multiple stock market anomalies into a composite score. For each of the three VOV variables, we assign a rank to each stock option that reflects the sorting on that

[13] Note that we consider the return of buying delta-hedged options in the regression analysis, while we consider the return of selling the delta-hedged options in the portfolio analysis. Lakonishok et al. (2007) and Gârleanu et al. (2009) document that end users are net sellers in the equity option market.

[14] The results are qualitatively the same when we sort the equity options into decile portfolios. The results are available upon request.

VOV variable. The higher the rank, the lower the expected delta-hedged option returns, as reported in the Fama-Macbeth regression in the previous section. The composite rank is then the arithmetic average of its ranking percentile of the three VOV variables. We also use two weighting schemes to calculate the average option returns: equal weighting (EW) and option open interest weighting (OW) which weights by the market value of the option open interests at the beginning of the holding period.

Table 9 Panel B reports the average return for each quintile portfolio and the return spread of the top and bottom quintile portfolios. We report Newey-West (1987) t-statistics to adjust for serial correlations. We find that the portfolio returns increase monotonically from quintile 1 to 5 for the four VOV measures in both weighting schemes. For the EW weighting scheme, the (5-1) spread portfolios ranked by IMPLIED-VOV, EGARCH-VOV, and INTRADAY-VOV report monthly returns of 0.88%, 0.52%, and 0.47% with corresponding t-statistics of 13.77, 10.46, and 5.28. The option open interest weighting scheme generates a higher return spread for all four VOV measures, suggesting that the VOV effects are not driven by illiquid stock options.

For the combined-VOV we find that the magnitudes of the return spread and the t-statistics are higher thatn those of the individual VOV variables. Specifically, the return spread using EW (OW) weighting scheme is 0.92% (1.06%) per month with t-statistics 15.62 (15.03). In summary, we find that the three VOV variables can all predict delta-neutral call writing returns and that the combination of the three variables can further improve the performance of the strategy.

3.3.2. Risk adjusted returns of the return spread

The results of the Fama-Macbeth regressions and portfolio sorts establish a robust negative relation between VOV and expected delta-hedged option returns. The return spread of the VOV strategies could potentially be explained by some priced risk factor. We therefore examine whether the return of our option strategies can be explained by a set of existing common risk factors. We control for the Fama and French (1993)'s three factors, the momentum factor (Carhart (1997)), and Kelly and Jiang (2014)'s tail risk factor. We also control for two volatility factors: the zero-beta straddle return of the S&P 500 Index option (Coval and Shumway (2001)), and the change in VIX, the Chicago Board Options Exchange Market Volatility Index (Ang et al.

(2006)). We regress the VOV return spread portfolios, quintile 1 minus quintile 5, on the seven risk factors.

Table 9 Panel C shows reports raw returns and alphas on 3 pricing models of the VOV portfolio strategy that buys quintile 5 and sells quintile 1. After controlling for these risk factors, all of the alphas remain highly significant and are of similar magnitudes than the raw returns. We conclude that our option strategies based on VOV variables and combined VOV generate abnormal profits that are independent of the common risk factors in the stock market and two volatility risk factors.

4. Further Exploration of the Results

In this section we examine further interpretations of our results and we decompose the VOV measures to understand the implications of our findings. First, we examine whether our option returns are generated by earnings announcements. Second, we decompose VOV into a positive and a negative component. Positive VOV occurs when volatility increases and negative VOV occurs when volatility decreases. Third, we decompose VOV into systematic VOV and idiosyncratic VOV to understand the source of predictability.

4.1. The impact of earning announcements

As argued in Barberis and Thaler (2003) and Engelberg, McLean, and Pontiff (2018), return predictability potentially reflects mispricing. The marginal investor may have biased expectations of volatility and VOV could relate to these mistakes across stocks. When new information arrives such as the earning announcements, investors update their beliefs and correct the mispricing, creating the return predictability. Engelberg et al. (2018) find that anomaly returns are 6 times higher on earning announcement days for 97 stock return anomalies. They also find that the results are most consistent with the explanation of biased expectations.

We now examine to which extent the VOV effect takes place during earnings announcement days using two approaches. In the first approach we perform the analysis on non-earnings announcement months to assess if the returns are still significant. In the second approach we focus on the earnings announcement month to compare the option return around the earnings announcement date (1 day before to 1 day after the announcement) with the return for the rest of that month.

Table 10 reports the 5-1 return spread for firm-months across earnings announcement subsets. The 5-1 return spread is computed from a long position in quintile 5 and a short position in quintile 1 with portfolios ranked on the three VOV measures. The return is calculated from the daily rebalanced and compounded return of the delta-neutral call writing strategy. For reference, we first report the long-short option returns that are the same than those in the last column of Table 9, Panel B. In the next column we report the 5-1 return spread by excluding the months with earnings announcements. The 5-1 return spread is of similar magnitude than the one for the full sample.

The last three columns of Table 10 only focus on the earnings announcement month. The 5-1 return spread is also positive and significant when we only include the months with earnings announcement. However the returns are smaller in the months with earnings announcements. Finally we split the 5-1 return spread between the three day window around the earnings announcement date [-1, 1] and the other days of the month. We find that the magnitude of the return spread over the [-1, 1] event window is small and insignificant, while the return spread over the other days of the month is significant.

We conclude that the VOV effect is mostly present in periods without earning announcement. These results indicate that the news about earning announcements does not drive the VOV effect in the equity option market. Hence, the VOV effect does not seem to arise from biased expectations.

[Insert Table 10 about here]

4.2. Volatility of positive and negative percentage changes of volatility

So far our results show that volatility-of-volatility (VOV) predicts future option returns. If we think of VOV as a measure of how difficult it is for the option writer to hedge an option position, positive changes of volatility should impact option valuation differently than negative changes of volatility. Option writers should be more concerned with positive changes of volatility because it leads to potential losses. Hence, the volatility of positive volatility changes (VOV+) might have a larger impact on future option returns than the volatility of negative volatility changes. To test this hypothesis, we calculate VOV+ as the volatility of positive volatility percentage changes over the past month, VOV- as the volatility of negative volatility percentage changes over the past month.

Table 11 reports the Fama-Macbeth regression results for different specifications of VOV+ and VOV-. Panel A and B show univariate regression results of VOV+ and VOV-, respectively. Our hypothesis that VOV+ has a larger effect on option returns than VOV- is supported by the dominating effect of VOV+ computed for implied volatility. The coefficient of IMPLIED VOV+ is highly negative and significant with t-statistics -6.78, while the coefficient of IMPLIED VOV- is positive and not statistically significant. Panel C of Table 11 reports joint regressions of VOV+ and VOV-. In this case, both coefficients are significant, hence VOV+ and VOV- do not subsume information of each other. The one for VOV+ is negative and highly significant and that for VOV- is now positive and significant.

The hypothesis is not supported by VOV+ and VOV- based on EGARCH and INTRADAY volatilities. In both cases, the coefficient of VOV- is larger (in absolute value) than the one of VOV+. However, both VOV+ and VOV- significantly predict future delta-hedged option returns. Joint regressions with VOV+ and VOV- in Panel C confirm these findings. Once again, VOV+ and VOV- do not subsume information of each other. Overall, these results suggest that option writers tend to use IMPLIED volatility, instead of realized (such as EGARCH or INTRADAY) volatilities, to price options.

[Insert Table 11 about here]

We now discuss a potential explanation for the asymmetric effect of IMPLIED-VOV+ and IMPLIED-VOV- on option returns. Lakonishok, Lee, Pearson, and Poteshman (2007) and Gârleanu et al. (2009) find that for both calls and puts, nonmarket maker investors in aggregate have more written than purchased open interest, implying that end-users are net short single-stock options. For option writers, hedging is necessary because the risk of naked call option writing is unlimited and because they are required by brokers to cover their positions. These end users are more concerned with options with high IMPLIED-VOV+ for two reasons: 1) they are considered to be difficult to hedge because the historical movement of volatility is volatile, and 2) high IMPLIED-VOV+ options may be more likely to experience large volatility increases in the future, leading to higher potential losses. Consequently, option writers charge a higher price for high VOV+ options that translates into lower option returns in the future. Option writers are less concerned about high VOV- options. Although these options are still difficult to hedge, they are likely to experience volatility decreases in the future, leading to potential gains. Moreover, option buyers are not willing to buy an expensive option with high VOV- due to the potential future loss. Hence, the option writers charge a high price for high VOV+ options and charge a not-so-high price for high VOV- options, which creates the asymmetric return predictability.

Why does the asymmetric effect not hold for EGARCH and INTRADAY volatilities? End users are usually not as sophisticated as market makers in the equity option market, who have more access and resources to market information. For the end-users, information about implied volatility is more straightforward and easier to obtain than information about realized volatility, which requires model estimation, availability of high frequency data and essentially comes from a different market. EGARCH-VOV and INTRADAY-VOV are too costly for them to pay attention to. However, market makers use many different realized volatility models with daily and intraday return data to help forecast volatility and manage risk exposure. They also care less about the direction of the movement of volatility. High volatility of positive volatility and high volatility of negative volatility are equally unfavorable to them because they intend to hedge their position and minimize their inventory risk. Hence, for these two realized volatility measures, they charge a premium for options with either high VOV+, or high VOV-, leading to lower future option returns.

To further understand the predictability of VOV, we study the signed jump of variance (JOV) defined as the square of VOV+ minus the square of VOV- divided by the square of VOV as in Patton and Sheppard (2015). Panel D of Table 10 shows bivariate regression results of VOV and JOV. Regression results confirm the negative and significant relation between VOV and option returns. In addition, JOV predicts future delta-hedged option returns in addition to VOV. The three JOVs are all statistically significant in the bivariate regressions. The effect of IMPLIED-JOV is stronger and more negative than the effect of the other two JOV measures, suggesting that option writers pay attention to implied volatility more than to EGARCH and INTRADAY volatilities.

4.3. Volatility of Systematic volatility and idiosyncratic volatility

In this section we decompose VOV into its systematic and idiosyncratic components.[15] To measure idiosyncratic volatility for each stock i, we run the Fama-French 3-factor model as follows

$$r_{i,t} = \alpha_i + \beta_{i,MKT}MKT_t + \beta_{i,SMB}SMB_t + \beta_{i,HML}HML_t + \varepsilon_{i,t}$$

Where $r_{i,t}$ is the daily return of stock i, and MKT_t, SMB_t and HML_t are the Fama-French factors. We estimate the model assuming that $\varepsilon_{i,t}$ follows an EGARCH (1,1) process.[16] Using the EGARCH (1,1) model we get a time varying measure of idiosyncratic volatility, $\sigma_{\varepsilon_i,t}$.

To measure systematic volatility for each stock i, we first estimate the daily total volatility $\sigma_{TOT_i,t}$ with an EGARCH (1,1) model using a rolling window of 252 historical daily returns, $r_{i,t}$. We define daily systematic volatility as

$$\sigma_{sys_i,t} = \sqrt{\sigma^2_{TOT_i,t} - \sigma^2_{\varepsilon_i,t}}$$

Using one month of daily volatilities, we calculate the volatility-of-idiosyncratic-volatility as the standard deviation of the daily percentage change of $\sigma_{\varepsilon_i,t}$ and the volatility-of-systematic-volatility as the standard deviation of the daily percentage change of $\sigma_{sys_i,t}$.

Table 12 reports the Fama-Macbeth regressions of delta-hedged option returns on EGARCH-VOV, volatility-of-systematic-volatility, and volatility-of-idiosyncratic-volatility. The first regression reproduces the results from Table 3. In regressions 2 to 4, the coefficients of volatility-of-idiosyncratic-volatility and volatility-of-systematic-volatility are both negative and statistically significant in the univariate and bivariate regressions. More important, the coefficients of volatility-of-idiosyncratic-volatility are 10 times larger than those of volatility-of-systematic-volatility. This result implies that only hedging systematic risk leaves the largest risk, idiosyncratic risk, unhedged.

We argue that stock options with high uncertainty in idiosyncratic volatility are more difficult to hedge than those with high uncertainty in systematic volatility. The movement of

[15] This decomposition is only available for EGARCH volatility, because the idiosyncratic EGARCH volatility can be estimated using EGARCH (1,1) model with Fama-French 3-factor. The idiosyncratic volatility is not available at the daily frequency for the other two volatility measures.
[16] Fu (2009) and Cao and Han (2016) also use exponential GARCH models to estimate idiosyncratic volatility with historical monthly and weekly stock returns data, respectively.

systematic volatility in an option portfolio can be hedged with VIX futures or index options, while the hedging of firm-specific volatility is more difficult to implement. This evidence is consistent with the explanation that option sellers demand a high price for option with high VOV because they are difficult to hedge.

[Insert Table 12 about here]

4.4. Systematic and idiosyncratic components of volatility changes

In the Intertemporal-CAPM model, assets with high sensitivity to innovations in aggregate volatility have low average return, which has been confirmed in the stock market by Ang et al. (2006). To test whether the VOV effect is consistent with a risk-based explanation, we decompose the daily change of implied volatility and EGARCH volatility into the exposure to the percentage change in market volatility and an idiosyncratic component.

To decompose the daily change of implied volatility, we use the implied volatility of each stock, σ_t, and the VIX index, σ_{mt}. To decompose the daily change of EGARCH volatility, we estimate daily volatility using an EGARCH (1,1) model with a rolling window of 252 days for each stock, σ_t, and for the S&P 500 index, σ_{mt}. We then run the following regression using daily data in each month:

$$\frac{\Delta\sigma_t}{\sigma_t} = \alpha + \beta\frac{\Delta\sigma_{mt}}{\sigma_{mt}} + \epsilon_t$$

$\hat{\beta}$ is defined as the systematic exposure to the percentage change of σ_{mt} (Beta to (%Δ in MKT Vol)). The RMSE of $\widehat{\epsilon_t}$ is defined as the idiosyncratic volatility of the change in volatility (Vol of (idio %Δ in Vol)).

Table 13 reports the Fama-Macbeth regressions of delta-hedged call option returns on VOV, its beta with respect to the market VOV, and the idiosyncratic VOV. The coefficient of Vol of (idio %Δ in Vol) is negative and significant in regressions 3 and 4 for both VOV specifications. In addition, the coefficients for IMPLIED-VOV are 2-3 times larger than the ones for EGARCH-VOV. Regressions 2 and 4 for IMPLIED-VOV and EGARCH-VOV report a positive and significant coefficient for the Beta to (%Δ in MKT Vol). The positive sign of the systematic exposure is not consistent with ICAPM, indicating that a risk-based explanation unlikely explains the VOV effect.

[Insert Table 13 about here]

4.5. Systematic and idiosyncratic components of VOV

In the third method, we do a robustness check of the second decomposition by decomposing the EGARCH-VOV into exposure to market VOV and residual VOV. For each stock, we first estimate daily volatility using a EGARCH (1,1) model with a rolling window of 252 days for each stock (σ_t) and for S&P 500 index (σ_{mt}). For each month and each stock, we run the following regression with monthly data of the past 36 months:

$$vol\ of\ \frac{\Delta\sigma_t}{\sigma_t} = \alpha + \beta\ vol\ of\ \frac{\Delta\sigma_{mt}}{\sigma_{mt}} + \epsilon_t$$

We then get $\hat{\beta}$ and the time series of residual $\widehat{\epsilon_t}$. $\hat{\beta}$ is defined as the systematic exposure to market volatility of percentage change of σ_{mt} (Beta to MKT-VOV). RMSE of $\widehat{\epsilon_t}$ is defined as the residual volatility of the change in volatility (Residual_VOV).

Table 14 reports the Fama-Macbeth regressions of delta-hedged call option returns on the VOV beta and the residual VOV. The coefficients of the VOV beta are not consistent in any specification. In two equations the coefficients are positive and in the other two they are negative. The residual VOV coefficients are consistently negative and significant in all specifications. As in the previous specification, the coefficients for IMPLIED-VOV are 2-3 times larger than the ones for EGARCH-VOV.

We conclude that the VOV effect cannot be explained by a risk-based theory. Using three different approaches, we decomposed VOV into a systematic and an idiosyncratic component and the results do not support a risk based explanation. The results are more consistent with the conjecture that option writers charge a high price for stock options with high idiosyncratic exposure which is difficult to hedge.

[Insert Table 14 about here]

5. Conclusion

This paper documents a robust negative relation between volatility-of-volatility and future delta-hedged option returns. Our results suggest that option writers tend to charge a higher premium for equity options whose volatility is difficult to forecast and consequently are difficult to hedge. We measure the daily volatility using three methodologies: implied volatility, EGARCH volatility estimated from daily stock returns, and intraday volatility calculated from five-minute high frequency returns. The volatility-of-volatility is then calculated for each month based on the three volatility estimates to get: EGARCH-VOV, IMPLIED-VOV, and INTADAY-VOV. The three VOV measures have low cross-sectional correlations, suggesting that they cover different information sets.

The negative effect of VOV is significant and robust to different sets of control variables including liquidity measures, volatility-related mispricing measures, and jump risk measures. The results cannot be explained by firm-level information uncertainty, variables of asymmetry, or by stock characteristics that predict option returns. Motivated by the regression results, we construct tradable option portfolios ranked by the three VOV measures and study future delta-neutral call writing returns. These option portfolio strategies deliver positive average returns that cannot be explained by common risk factors from the stock market nor by two volatility risk factors.

To understand the sources of the VOV predictability, we explore several potential explanations. First, we find that the return spread is not generated around earnings announcements. Second, we decompose VOV into positive VOV (VOV+) and negative VOV (VOV-). We find that VOV+ of implied volatility has a much larger impact on future option returns than VOV-. This result is consistent with option writers disliking VOV+ more than VOV- for implied volatility; however, for two realized volatility measures, market makers charge a premium to compensate for hedging cost, for options with either high VOV+, or high VOV-.

Lastly, we find that most of the predictability is driven by the idiosyncratic components of VOV and not by its systematic component. The results suggest that the VOV effect is difficult to be reconciled with classic risk-based theories such as the arbitrage pricing model or ICAPM model. The findings are more consistent with the explanation that options with high volatility of idiosyncratic volatility are more difficult to hedge for the market maker.

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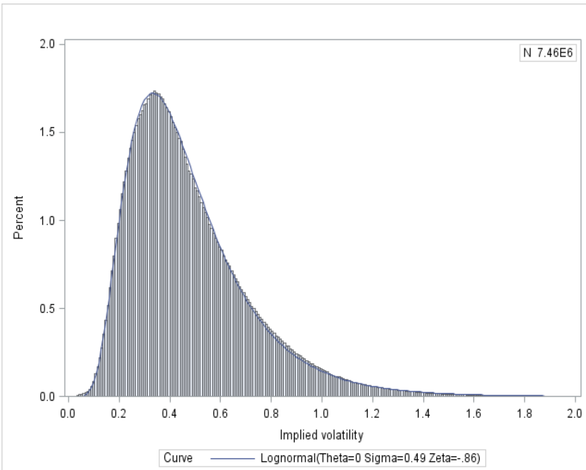
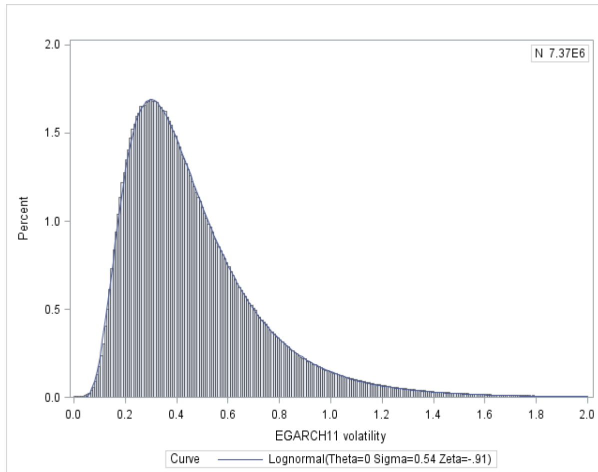
Figure 1. Distribution of daily volatility level and the percentage change of volatility (Δσ/σ)

This table presents the histograms of the daily level and percentage change of the three measures of volatility estimator for the stocks in our sample during the period of January 1996 to April 2016. Figures for the distribution of EGARCH volatility, Implied Volatility, and Intraday volatility are reported in (a), (b), and (c), respectively. Figures for the distribution of the percentage change of the three measures of volatility are reported in (e), (f), and (g), respectively.

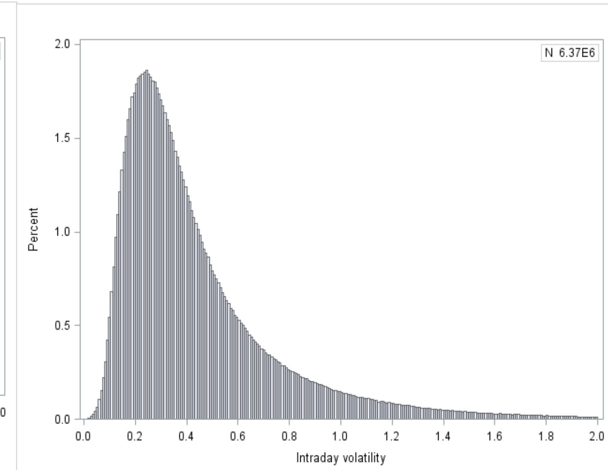
(a) Implied Vol



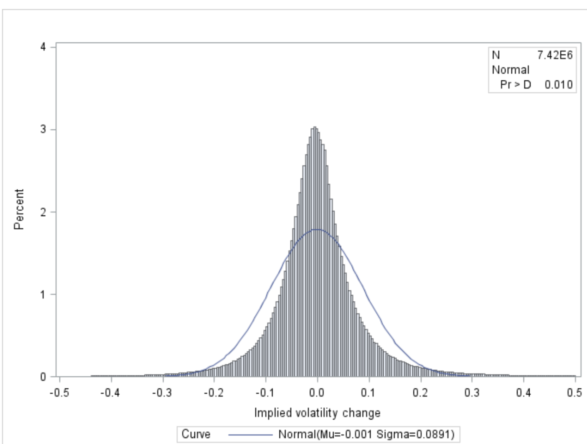
(b) EGARCH Vol



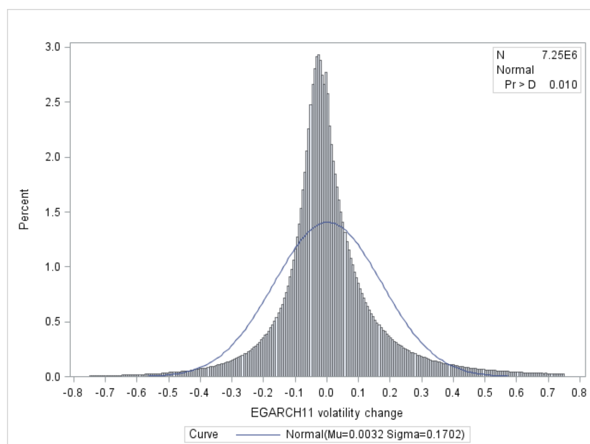
(c) Intraday Vol



(d) Change of Implied Vol



(e) Change of EGARCH Vol



(c) Change of Intraday Vol

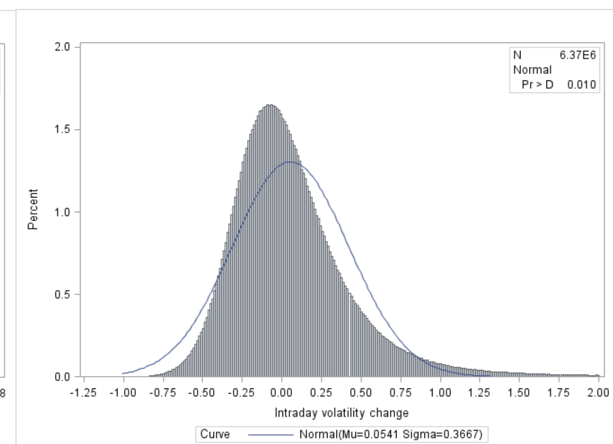


Table 1: Summary Statistics

This table reports the descriptive statistics of delta-hedged option returns. The option sample period is from January 1996 to April 2016. Panels A and B report call and put option delta-hedged gains over the initial investment. The delta-hedged gain is the change over one month or until maturity in the value of a portfolio consisting of one contract of a long call (put) position minus a delta amount on the underlying stock. The delta hedge is rebalanced daily. The initial investment is (Δ*S-C) for calls and (P-Δ*S) for puts, where Δ is the Black-Scholes option delta, S is the underlying stock price, and C (P) is the call (put) option price. Moneyness is the ratio of the stock to option strike price. Days to maturity is the number of calendar days until the option expiration. Vega is the option vega according to the Black-Scholes model scaled by the stock price. 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. All of these variables are winsorized each month at the 0.5% level.

Variables		Mean	Standard deviation	10th percentile	Lower quartile	Median	Upper quartile	90th percentile
Panel A: Call Options (327,016 observations)								
Delta-hedged gain till month-end / (Δ*S – C)	(%)	-0.82	4.90	-5.08	-2.66	-0.89	0.75	3.28
Delta-hedged gain till maturity / (Δ*S – C)	(%)	-1.11	7.58	-7.20	-3.69	-1.22	0.92	4.27
Moneyness = S/K	(%)	100.53	4.79	95.13	97.78	100.16	102.93	106.13
Days to maturity		50	2	47	50	50	51	52
Vega		0.14	0.01	0.13	0.14	0.14	0.15	0.15
Quoted option bid-ask spread (%)		19.29	15.56	5.57	8.80	14.65	24.77	39.19
Panel B: Put Options (305,710 observations)								
Delta-hedged gain till maturity / (P - Δ*S)	(%)	-0.48	4.36	-4.33	-2.33	-0.76	0.83	3.36
Delta-hedged gain till month-end / (P - Δ*S)	(%)	-0.82	7.69	-6.20	-3.31	-1.14	0.95	4.31
Moneyness = S/K	(%)	99.82	4.56	94.55	97.27	99.81	102.25	105.16
Days to maturity		50	2	47	50	50	51	52
Vega		0.14	0.01	0.13	0.14	0.14	0.15	0.15
Quoted option bid-ask spread (%)		20.53	16.36	5.96	9.48	15.61	26.39	41.54

Table 2: Summary Statistics of Moments of Volatility Changes

This table reports the descriptive statistics of volatility-of-volatility (VOV), skewness-of-volatility (SOV) and kurtosis-of-volatility (KOV). In Panel A, B, and C, VOV, SOV and KOV are the volatility, skewness and kurtosis of the percentage change of volatility ($\Delta\sigma/\sigma$) in each month. Panel D reports the correlation matrix of the 3 VOV measures. Under each definition, we calculate volatility moments using three measures of volatility. Panel A is based on the daily at-the-money implied volatility (delta=50) from the volatility surface file provided by OptionMetrics IvyDB database. Panel B is based on daily volatility estimated using an EGARCH model. Each month for each stock, the daily realized volatility is estimated from the EGARCH (1,1) model using a rolling window of daily returns over the past 12-month. Panel C is based on the daily intraday volatility calculated with five-minute log returns provided by TAQ.

Variable	Mean	Standard Deviation	10th percentile	Lower Quartile	Median	Upper Quartile	90th percentile
Panel A: Based on Daily Option Implied Volatility, 324,765 observations							
Vol level σ	0.48	0.25	0.23	0.30	0.43	0.60	0.80
VOV (Vol of $\Delta\sigma/\sigma$)	0.09	0.08	0.04	0.05	0.07	0.10	0.15
SOV (Skew of $\Delta\sigma/\sigma$)	0.22	0.96	-0.84	-0.29	0.21	0.73	1.35
KOV (Kurt of $\Delta\sigma/\sigma$)	1.34	2.64	-0.84	-0.34	0.51	2.03	4.57
Panel B: Based on EGARCH (1,1) Daily Return Volatility, 304,884 observations							
Vol level σ	0.47	0.30	0.20	0.28	0.40	0.58	0.82
VOV (Vol of $\Delta\sigma/\sigma$)	0.19	0.23	0.05	0.08	0.13	0.23	0.38
SOV (Skew of $\Delta\sigma/\sigma$)	0.89	1.05	-0.28	0.24	0.83	1.51	2.24
KOV (Kurt of $\Delta\sigma/\sigma$)	1.98	3.34	-0.87	-0.25	0.90	3.02	6.33
Panel C: Based on 5-Min Intraday Return Volatility, 277,678 observations							
Vol level σ	0.45	0.34	0.16	0.23	0.35	0.55	0.86
VOV (Vol of $\Delta\sigma/\sigma$)	0.39	0.20	0.23	0.27	0.35	0.45	0.59
SOV (Skew of $\Delta\sigma/\sigma$)	0.94	0.85	0.02	0.37	0.81	1.38	2.09
KOV (Kurt of $\Delta\sigma/\sigma$)	1.59	3.20	-0.93	-0.45	0.48	2.37	5.76

Panel D: Correlation Matrix of Three Volatility-of-Volatility Measures

	EGARCH-VOV	INTRADAY-VOV
IMPLIED-VOV	0.07	0.08
EGARCH-VOV		0.12

Table 3: Delta-Hedged Option Returns and Volatility-of-Volatility

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns for call and put options. We use 3 volatility-of-volatility (VOV) measures. IMPLIED-VOV is calculated using daily at-the-money implied volatility (delta=50) from the volatility surface file provided by OptionMetrics IvyDB database. EGARCH-VOV is calculated based on daily volatility estimated using an EGARCH model. Each month for each stock, the daily realized volatility is estimated from the EGARCH (1,1) model using a rolling window of daily returns over the past 12 months. INTRADAY-VOV is calculated using daily intraday volatility calculated with five-minute returns from TAQ database. VOV is defined as the standard deviation of percentage change of volatility ($\Delta\sigma/\sigma$) in each month. Panel A reports the delta-hedged gain until month end / (Δ*S - C), and Panel B reports four definitions of option returns: (1) delta-hedged gain till month-end / stock price, (2) delta-hedged gain till month-end / option price, (3) delta-hedged gain till maturity / (Δ*S - C), and (4) delta-hedged gain till week end / (Δ*S - C). All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Panel A: Delta-hedged option return and volatility-of-volatility

Fama-Macbeth	Call Options				Put Options			
Regressions	Delta-hedged gain till month end / (Δ*S-C)				Delta-hedged gain till month end / (P-Δ*S)			
IMPLIED-VOV	-3.002***			-2.830***	-1.552***			-1.309***
	(-6.30)			(-5.43)	(-3.88)			(-2.92)
EGARCH-VOV		-0.988***		-0.818***		-0.746***		-0.649***
		(-10.08)		(-7.51)		(-11.10)		(-9.20)
INTRADAY-VOV			-1.110***	-0.954***			-0.908***	-0.826***
			(-6.53)	(-5.64)			(-7.04)	(-6.38)
Intercept	-0.555***	-0.600***	-0.336**	-0.060	-0.422***	-0.389***	-0.174	-0.012
	(-4.64)	(-5.05)	(-2.54)	(-0.45)	(-3.69)	(-3.26)	(-1.37)	(-0.10)
Adj. R^2	0.003	0.002	0.004	0.009	0.003	0.002	0.004	0.008

Panel B: Alternative dependent variables

	Call Options				Put Options			
	Gain till month	Gain till month	Gain till maturity	Gain till week	Gain till month	Gain till month	Gain till maturity	Gain till week
	Stock price	Option price	(Δ*S - C)	(Δ*S - C)	Stock price	Option price	(Δ*S - C)	(Δ*S - C)
IMPLIED-VOV	-0.771***	3.690*	-4.494***	-0.736***	-0.529***	-2.415***	-0.765***	-0.105***
	(-6.52)	(-4.79)	(-8.02)	(-3.05)	(-8.38)	(-6.09)	(-7.89)	(-3.85)
IMPLIED-VOV	-0.771***	3.690*	-4.494***	-0.736***	-0.781**	7.963**	-1.723***	0.119
	(-4.42)	(1.85)	(-6.58)	(-2.98)	(-2.04)	(2.20)	(-2.99)	(0.76)
INTRADAY-VOV	-0.350***	-4.627***	-1.145***	-0.179***	-0.750***	-4.538***	-0.975***	-0.161***
	(-5.22)	(-7.42)	(-4.95)	(-3.99)	(-6.32)	(-6.75)	(-5.30)	(-4.30)
Intercept	-0.090	-2.053***	-0.023	0.179***	-0.092	-1.570	-0.250	0.180***
	(-1.44)	(-2.21)	(-0.13)	(3.27)	(-0.75)	(-1.51)	(-1.43)	(3.83)
Adj. R^2	0.009	0.006	0.007	0.008	0.008	0.006	0.006	0.006

Table 4: Control for Volatility-Related Measures, Volatility Risk Premium, and Jump Risk

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month end for call options. IMPLIED-VOV, EGARCH-VOV and INTRADAY-VOV are calculated using three measures of volatility as described in Table 3. VOV is defined as standard deviation of the percentage change in volatility in the previous month. IVOL is the annualized stock return idiosyncratic volatility defined in Ang, Hodrick, Xing and Zhang (2006). VOL_deviation is the log difference between the realized volatility and the Black-Scholes implied volatility for at-the-money options at the end of last month as in Goyal and Saretto (2009). Realized volatility is the standard deviation of stock returns estimated from daily data over the previous month. VTS slope is the difference between the long-term and short-term volatility defined in Vasquez (2017). The volatility risk premium (VRP) is defined as the difference between the square root of realized variance estimated from intraday stock returns over the previous month and the square root of a model free estimate of the risk-neutral volatility. Jump_left (Jump_right) is the model-free left/right jump tail measure calculated by option prices defined in Bolleslev and Todorov (2011). Implied skewness is the risk-neutral skewness of stock returns as in Bakshi, Kapadia, and Madan (2003). Volatility spread is the implied volatility difference between ATM call and put options. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Panel A: Control for volatility-related measures

Fama-Macbeth Regressions	Call Options Delta-hedged gain till maturity (Δ^*S-C)			
IMPLIED-VOV	-1.703***			-2.076***
	(-3.75)			(-4.21)
EGARCH-VOV		-0.715***		-0.632***
		(-6.35)		(-5.51)
INTRADAY-VOV			-0.536***	-0.458***
			(-4.09)	(-3.62)
IVOL	-4.731***	-4.672***	-4.565***	-4.451***
	(-27.09)	(-26.93)	(-25.20)	(-23.83)
VOL_deviation	4.037***	4.088***	3.945***	3.981***
	(19.77)	(20.06)	(19.71)	(19.44)
VTS slope	5.043***	5.105***	5.138***	4.996***
	(13.44)	(13.77)	(13.03)	(12.66)
Intercept	1.506***	1.514***	1.528***	1.694***
	(11.84)	(12.90)	(13.87)	(13.16)
Adj. R^2	0.097	0.096	0.096	0.099

Table 4 (Continued)

Panel B: Control for volatility risk premium

Fama-Macbeth Regressions	Call Options			
	Delta-hedged gain till maturity (Δ^*S-C)			
IMPLIED-VOV	-4.828***			-3.984***
	(-5.97)			(-5.16)
EGARCH-VOV		-1.215***		-0.933***
		(-11.34)		(-8.58)
INTRADAY-VOV			-1.583***	-1.407***
			(-9.64)	(-8.89)
VRP	7.928***	7.794***	7.917***	8.140***
	(16.84)	(15.95)	(15.52)	(16.59)
Intercept	0.000	-0.111	0.342***	0.700***
	(0.00)	(-0.95)	(2.63)	(5.73)
Adj. R^2	0.045	0.044	0.046	0.052

Panel C: Control for jump risk

IMPLIED-VOV	-1.149**			-0.272**
	(-2.19)			(-2.49)
EGARCH-VOV		-0.413***		-1.041**
		(-3.69)		(-2.11)
INTRADAY-VOV			-0.750***	-0.677***
			(-5.34)	(-4.94)
Jump_left	-2.117***	-2.140***	-2.123***	-2.114***
	(-7.01)	(-7.03)	(-7.09)	(-7.06)
Jump_right	-1.768***	-1.717***	-1.662***	-1.638***
	(-7.44)	(-7.06)	(-6.91)	(-6.76)
Implied skewness	-0.044***	-0.040**	-0.035**	-0.036**
	(-2.68)	(-2.32)	(-1.97)	(-2.05)
Volatility spread	10.359***	10.284***	10.493***	10.552***
	(18.42)	(18.33)	(19.33)	(19.42)
Intercept	0.120	0.133	0.349**	0.416***
	(0.90)	(1.02)	(2.55)	(2.83)
Adj. R^2	0.087	0.088	0.089	0.091

Table 5: Control for Liquidity and Option Demand Pressure

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month end for both call options and put options. IMPLIED-VOV, EGARCH-VOV and INTRADAY-VOV are calculated using three measures of volatility as described in Table 3. VOV is defined as standard deviation of percentage change in volatility in the previous month. Option bid-ask spread is the ratio of the difference between the bid and ask quotes of option to the midpoint of the bid and ask quotes at the end of previous month. Ln (Amihud) is the natural logarithm of illiquidity, calculated as the average of the daily Amihud (2002) illiquidity measure over the previous month. Option demand pressure is calculated as (Option open interest / stock volume) ×10^3. Option open interest is the total number of option contracts that are open at the end of the previous month. Stock volume is the stock trading volume over the previous month. Ln (total size of all Calls) is the log of the total market value of the open interest of all call option in the previous month. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Fama-Macbeth Regressions	Call Options			
	Delta-hedged gain till month end (Δ*S-C)			
IMPLIED-VOV	-2.140***			-2.356***
	(-4.33)			(-4.35)
EGARCH-VOV		-0.688***		-0.558***
		(-6.95)		(-5.51)
INTRADAY-VOV			-0.750***	-0.627***
			(-4.29)	(-3.63)
Option bid-ask spread	0.058	-0.051	-0.047	0.112
	(0.28)	(-0.24)	(-0.22)	(0.51)
Ln (Amihud)	-0.590***	-0.591***	-0.600***	-0.582***
	(-18.53)	(-18.31)	(-17.02)	(-17.09)
Option demand pressure	-1.855***	-1.887***	-2.081***	-2.128***
	(-5.13)	(-5.33)	(-5.00)	(-5.13)
Ln (total size of all Calls)	-0.278***	-0.278***	-0.271***	-0.265***
	(-18.68)	(-19.13)	(-17.82)	(-16.77)
Intercept	-2.220***	-2.216***	-2.207***	-1.972***
	(-9.97)	(-9.80)	(-7.89)	(-7.32)
Adj. R^2	0.056	0.055	0.057	0.062

Table 6: Control for Stock Information Uncertainty and Asymmetry

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month end for both call options and put options. IMPLIED-VOV, EGARCH-VOV and INTRADAY-VOV are calculated using three measures of volatility as described in Table 3. VOV is defined as standard deviation of percentage change in volatility in the previous month. Analyst coverage is the number of analysts following the firm in the previous month. Analyst dispersion is the Standard deviation of analyst forecasts in the previous month scaled by the prior year-end stock price. PIN is the probability of informed trading in Easley, Hvidkjaer, and O'hara (2002). All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Fama-Macbeth Regressions	Call Options Delta-hedged gain till month end (Δ*S-C)			
IMPLIED-VOV	-1.821***			-2.126***
	(-3.79)			(-3.69)
EGARCH-VOV		-0.747***		-0.594***
		(-8.46)		(-6.70)
INTRADAY-VOV			-0.801***	-0.694***
			(-4.35)	(-3.77)
Analyst coverage	0.025***	0.025***	0.022***	0.020***
	(6.08)	(6.02)	(5.26)	(5.18)
Analyst dispersion	-0.261***	-0.272***	-0.285***	-0.282***
	(-5.44)	(-5.45)	(-5.58)	(-5.48)
Stock PIN	-0.414***	-0.428***	-0.336**	-0.259*
	(-2.81)	(-3.02)	(-2.34)	(-1.78)
Intercept	-0.720***	-0.704***	-0.507***	-0.304*
	(-4.66)	(-4.59)	(-2.87)	(-1.79)
Adj. R^2	0.013	0.011	0.014	0.019

Table 7: Control for Firm Characteristics

This table reports the average coefficients from Fama-MacBeth regressions of delta-hedged option returns until month end for call options. IMPLIED-VOV, EGARCH-VOV and INTRADAY-VOV are calculated using three measures of volatility as described in Table 3. VOV is defined as the standard deviation of the percentage change in volatility in the previous month. Size is the logarithm of market capitalization in billions of U.S. dollars. $RET_{(-1,0)}$ is the lagged one month return. $RET_{(-12,-2)}$ is the cumulative returns over months 2 to 12 prior to the current month. CH is the cash-to-assets ratio as in Palazzo (2012). ISSUE represents new issues as in Pontiff and Woodgate (2008). PROFIT is the profitability as in Fama and French (2006). All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Fama-Macbeth Regressions	Call Options			
	Delta-hedged gain till month end (Δ*S-C)			
IMPLIED-VOV	-1.240***			-1.690***
	(-3.21)			(-4.20)
EGARCH-VOV		-0.645***		-0.535***
		(-6.98)		(-5.39)
INTRADAY-VOV			-0.691***	-0.608***
			(-4.58)	(-4.07)
Ln (ME)	0.207***	0.212***	0.208***	0.191***
	(9.67)	(9.82)	(8.77)	(8.55)
$RET_{(-1,0)}$	1.286***	1.294***	1.306***	1.302***
	(6.15)	(6.25)	(6.15)	(6.06)
$RET_{(-12,-2)}$	0.259***	0.257***	0.265***	0.262***
	(4.44)	(4.48)	(4.66)	(4.63)
CH	-1.058***	-1.029***	-0.928***	-0.934***
	(-7.00)	(-6.86)	(-5.90)	(-6.12)
ISSUE	-0.875***	-0.866***	-0.779***	-0.797***
	(-6.01)	(-5.90)	(-5.07)	(-5.23)
PROFIT	0.534***	0.540***	0.527***	0.519***
	(12.34)	(12.52)	(10.45)	(10.23)
Intercept	0.207***	-2.146***	-2.010***	-1.721***
	(9.67)	(-9.46)	(-7.28)	(-6.63)
Adj. R^2	1.286***	0.043***	0.046***	0.050***

Table 8: Higher Order Moments of Volatility (Change)

This table reports the average coefficients from Fama-MacBeth regressions of delta-hedged option returns until month end for call options. Volatility, skewness, and kurtosis of percentage change in volatility are calculated based on daily measures of EGARCH volatility, IMPLIED volatility and INTRADAY volatility as described in Table 3. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Fama-Macbeth Regressions	Call Options Delta-hedged gain till maturity (Δ*S-C)		
	IMPLIED	EGARCH	INTRA-DAY
Volatility of (Volatility % change)	-2.022***	-0.695***	-0.964***
	(-4.52)	(-6.82)	(-5.72)
Skewness of (Volatility % change)	-0.124***	0.059***	-0.089***
	(-7.58)	(3.20)	(-2.60)
Kurtosis of (Volatility % change)	-0.013*	-0.043***	0.025***
	(-1.84)	(-7.53)	(2.92)
Intercept	-0.574***	-0.605***	-0.351***
	(-4.52)	(-4.81)	(-2.66)
Adj. R^2	0.006	0.003	0.004

Table 9: Option Portfolio Returns and Alphas (Sorted on VOV)

This table reports average portfolio returns for quintile portfolios ranked by four measures of volatility-of-volatility (VOV): IMPLIED-VOV, EGARCH-VOV, INTRADAY-VOV, and Combined-VOV as described in Table 3. The Combined VOV is computed as the average of the ranking percentile of the 3 individual VOV measures. We report average delta-neutral call writing returns with equal weighting (EW) and open interest weighting (OW) which weights by the market value of the option open interest. Panel A reports summary statistics. Panel B reports the average delta-neutral call writing for each quintile portfolio and the return spread that longs quintile 5 and shorts quintile 1. Panel C reports 3-factor, 5-factor, and 7-factor alphas which are derived from the Fama-French 3-factor model, the 5-factor model which adds momentum and the zero-beta straddle return of the S&P 500 Index option from Coval and Shumway (2001), and the 7-factor model which adds the change in VIX and the Kelly and Jiang (2014) tail risk factor. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Panel A: Summary statistics of the return to covered calls till month end (with daily rebalance) (%)

Mean	Standard deviation	10^{th} percentile	Lower quartile	Median	Upper quartile	90^{th} percentile
1.37	5.75	-2.91	-0.26	1.32	3.34	6.17

Panel B: Portfolio returns sorted on VOV (%)

Sorted on	Weight	1	2	3	4	5	(5 -1)
IMPLIED-VOV	EW	0.89	1.09	1.26	1.54	1.77	0.88***
		(6.39)	(8.76)	(9.95)	(12.49)	(14.21)	(13.77)
	OW	0.93	1.12	1.31	1.63	1.97	1.04***
		(6.84)	(9.21)	(10.61)	(13.28)	(15.80)	(13.38)
EGARCH-VOV	EW	1.15	1.16	1.25	1.38	1.68	0.52***
		(8.48)	(9.28)	(10.27)	(10.92)	(13.62)	(10.46)
	OW	1.16	1.18	1.30	1.42	1.73	0.57***
		(8.67)	(9.53)	(10.93)	(11.85)	(14.08)	(9.95)
INTRADAY-VOV	EW	1.08	1.12	1.21	1.30	1.56	0.47***
		(8.63)	(8.34)	(8.47)	(9.16)	(9.98)	(5.28)
	OW	1.12	1.18	1.27	1.36	1.65	0.54***
		(9.34)	(8.88)	(8.84)	(9.80)	(11.34)	(6.35)
Combined-VOV	EW	0.85	1.04	1.20	1.39	1.77	0.92***
		(6.07)	(7.49)	(9.56)	(9.42)	(12.51)	(15.62)
	OW	0.89	1.09	1.27	1.46	1.96	1.06***
		(6.47)	(8.05)	(10.45)	(9.98)	(14.51)	(15.03)

Panel C: Alphas of the 5-1 return spread

Sorted on	Weight	Raw return		3-factor Alpha		5-factor Alpha		7-factor Alpha	
IMPLIED-VOV	EW	0.88***	(13.77)	0.88***	(13.64)	0.92***	(12.18)	0.89***	(11.62)
	OW	1.04***	(13.38)	1.04***	(12.99)	1.09***	(11.47)	1.07***	(10.16)
EGARCH-VOV	EW	0.52***	(10.46)	0.54***	(10.16)	0.56***	(8.43)	0.59***	(7.00)
	OW	0.57***	(9.95)	0.58***	(9.54)	0.60***	(7.82)	0.64***	(6.67)
INTRADAY-VOV	EW	0.47***	(5.28)	0.47***	(5.15)	0.48***	(4.58)	0.38***	(3.01)
	OW	0.54***	(6.35)	0.52***	(6.02)	0.52***	(4.94)	0.45***	(3.50)
Combined-VOV	EW	0.92***	(15.62)	0.92***	(14.67)	0.91***	(11.37)	0.90***	(11.31)
	OW	1.06***	(15.03)	1.06***	(14.10)	1.07***	(11.48)	1.08***	(11.29)

Table 10: Impact of Earnings Announcements on 5-1 Return Spread

This table reports the average equal weighted 5-1 return spread during months with and without earning announcements. The return is the daily rebalanced and compounded return of the delta-neutral call writing strategy. The first column reports the average return spread of all stocks for the full sample. The second column reports the average return spread in the months without earning announcement. The third column reports the average return spread in the months with earning announcement. The fourth column reports the average return spread over the three day event window [-1,1] in the months with earning announcement. The fifth column reports the average return spread over the other days in the event months. We report the return spread in each period for IMPLIED-VOV, EGARCH-VOV and INTRADAY-VOV. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

	All Stocks	Without Earning Events	With Earning Events		
	Full Month	Full Month	Full Month	Over [-1 ,1] Event window	Over other days in a month
IMPLIED-VOV	1.04***	1.04***	0.84***	0.10	0.87***
	(13.28)	(11.69)	(6.47)	(1.29)	(5.35)
EGARCH-VOV	0.57***	0.68***	0.34***	0.08	0.22**
	(9.94)	(10.08)	(2.99)	(1.00)	(2.18)
INTRADAY-VOV	0.53***	0.56***	0.44***	0.05	0.39***
	(6.32)	(5.93)	(3.42)	(0.73)	(3.27)

Table 11: Volatility of Positive and Negative Volatility Percentage Change

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month end for call options. VOV+ is defined as the volatility of positive volatility percentage changes and VOV- is defined as the volatility of negative volatility percentage changes in the past month. Jump of variance (JOV) is defined as the square of VOV+ minus the square of VOV-, divided by the square of VOV. Panel A and B show univariate regression results of VOV+ and VOV-, respectively. Panel C shows bivariate regression results of VOV+ and VOV-. Panel D shows bivariate regression results of VOV and JOV. Columns 2-4 and columns 6-8 show regression results for measures based on IMPLIED, EGARCH, and INTRADAY volatility. We report in brackets Newey-West (1987) t-statistics.

Panel A: VOV+

	IMPLIED	EGARCH	INTRADAY
Intercept	-0.006***	-0.006***	-0.006***
	(-5.06)	(-5.52)	(-4.41)
VOV+	-0.038***	-0.009***	-0.008***
	(-6.78)	(-11.07)	(-5.09)
Adj. R^2	0.005	0.002	0.003

Panel B: VOV-

	IMPLIED	EGARCH	INTRADAY
Intercept	-0.008***	-0.006***	-0.002
	(-6.82)	(-4.66)	(-1.30)
VOV-	0.004	-0.030***	-0.043***
	(0.51)	(-10.46)	(-8.08)
Adj. R^2	0.002	0.002	0.003

Panel C: VOV+ and VOV-

	IMPLIED	EGARCH	INTRADAY
Intercept	-0.008***	-0.006***	-0.002
	(-6.93)	(-4.90)	(-1.46)
VOV+	-0.066***	-0.007***	-0.005***
	(-7.84)	(-7.07)	(-3.68)
VOV-	0.085***	-0.014***	-0.031***
	(7.07)	(-4.13)	(-7.39)
Adj. R^2	0.008	0.003	0.004

Panel D: VOV and JOV

	IMPLIED	EGARCH	INTRADAY
Intercept	-0.007***	-0.006***	-0.004***
	(-5.42)	(-5.04)	(-3.22)
VOV	-0.013***	-0.008***	-0.011***
	(-3.46)	(-9.26)	(-6.34)
JOV	-0.006***	-0.001***	0.002**
	(-12.27)	(-5.46)	(2.54)
Adj. R^2	0.007	0.003	0.004

Table 12: Decomposition of Volatility Level

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month end for call options. The VOV measure is calculated with daily volatility estimated using EGARCH (1,1) model. For each stock, we first estimate daily total volatility σ_t with an EGARCH (1,1) model using a rolling window of 252 days. Then we estimate daily idiosyncratic volatility $\sigma_{\varepsilon,t}$ using an EGARCH (1,1) model with Fama-French 3 factors in the return equation of the model. Daily systematic volatility is then defined as $\sqrt{\sigma_{i,t}^2 - \sigma_{\varepsilon_i,t}^2}$. Volatility of idiosyncratic volatility is the standard deviation of the daily percentage change in $\sigma_{\varepsilon,t}$ in the past month. Volatility of systematic volatility is the standard deviation of the daily percentage change in systematic volatility in the past month. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Fama-Macbeth Regressions	Call Options Delta-hedged gain till month end (Δ*S-C)			
	(1)	(2)	(3)	(4)
EGARCH-VOV	-0.797***			
	(-7.83)			
EGARCH-VOV_{idio}		-0.869***		-0.822***
		(-5.62)		(-5.24)
EGARCH-VOV_{sys}			-0.079***	-0.068***
			(-4.56)	(-3.77)
Intercept	-0.600***	-0.574***	-0.654***	-0.536***
	(-4.73)	(-4.99)	(-5.47)	(-4.60)
Adj. R^2	0.002	0.001	0.001	0.004

Table 13: Decomposition of Volatility Percentage Change

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged call option returns until month end. To decompose the daily percentage change in implied volatility, we use implied volatility of each stock, σ_t, and the VIX index, σ_{mt}. To decompose the daily percentage change in EGARCH volatility, we first estimate daily volatility using an EGARCH(1,1) model with a rolling window of 252 days for each stock (σ_t) and for S&P 500 index (σ_{mt}). Every month, we then run the following regression for each stock using daily data: $\frac{\Delta\sigma_t}{\sigma_t} = \alpha + \beta\frac{\Delta\sigma_{mt}}{\sigma_{mt}} + \epsilon_t$. $\hat{\beta}$ is defined as the systematic exposure to the percentage change of σ_{mt}. RMSE of $\widehat{\epsilon_t}$ is defined as the idiosyncratic volatility of change in volatility. We report in brackets Newey-West (1987) t-statistics.

Fama-Macbeth Regressions	Delta-hedged gain till month end (Δ*S-C)							
	IMPLIED-VOV				EGARCH-VOV			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
VOV	-3.555***				-0.797***			
	(-7.24)				(-7.83)			
Beta to (%Δ in MKT Vol)		0.175**		0.203***		0.079***		0.076***
		(2.43)		(2.85)		(3.10)		(2.84)
Vol of (Idio %Δ in Vol)			-2.508***	-2.702***			-0.947***	-0.961***
			(-6.18)	(-6.95)			(-10.00)	(-9.82)
Intercept	-0.429***	-0.835***	-0.588***	-0.649***	-0.600***	-0.795***	-0.608***	-0.623***
	(-3.14)	(-7.63)	(-4.94)	(-5.60)	(-4.73)	(-6.97)	(-5.08)	(-5.22)
Adj. R^2	0.006	0.004	0.007	0.004	0.002	0.001	0.003	0.004

Table 14: Decomposition of Volatility-of-Volatility

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month end for call options. To decompose the daily percentage change in IMPLIED-VOV, we use implied volatility of each stock, σ_t, and the VIX index, σ_{mt}. To decompose the EGARCH-VOV, we first estimate daily volatility using a EGARCH(1,1) model with a rolling window of 252 days for each stock (σ_t) and for S&P 500 index (σ_{mt}). Every month, we then run the following regression for each stock using with monthly data over the last 36 months: $vol\ of\ \frac{\Delta\sigma_t}{\sigma_t} = \alpha + \beta\ vol\ of\ \frac{\Delta\sigma_{mt}}{\sigma_{mt}} + \epsilon_t$. We use the same methodology to deconponse IMPLIED-VOV. $\hat{\beta}$ is defined as the systematic exposure to market volatility of percentage change of σ_{mt} and the RMSE of $\hat{\epsilon_t}$ is defined as the residual volatility of the change in volatility. We report in brackets Newey-West (1987) t-statistics.

Fama-Macbeth Regressions	Delta-hedged gain till maturity (Δ*S-C)					
	IMPLIED-VOV			EGARCH-VOV		
Beta to MKT-VOV	0.043		-0.093**	0.052**		-0.050*
	(1.72)		(-1.98)	(2.21)		(-1.87)
Residual_VOV		-1.175***	-1.987***		-0.633***	-0.722***
		(-4.43)	(-4.40)		(-7.37)	(-7.22)
Intercept	-0.477***	-0.384***	-0.343**	-0.692***	-0.578***	-0.556***
	(-3.90)	(-3.12)	(-2.82)	(-5.69)	(-4.65)	(-4.45)
Adj. R^2	0.001	0.002	0.004	0.001	0.002	0.004

Supplementary Appendix for

Volatility Uncertainty and the Cross-Section of Option Returns

Jie Cao, Aurelio Vasquez, Xiao Xiao, and Xintong Zhan

Appendix: Variable Definitions

Measures of volatility-of-volatility (VOV)	
EGARCH-VOV	The standard deviation of the percent change in daily realized stock volatility over the previous month. Each month for each stock, the daily realized volatility is estimated from the EGARCH (1,1) model using a rolling window of daily returns over the past 12-month.
IMPLIED-VOV	The standard deviation of the percent change in daily implied volatility with 30 days of maturity over the previous month. We use the at-the-money implied volatility (delta=50) from the volatility surface file provided by OptionMetrics.
INTRADAY-VOV	The standard deviation of the percent change in daily intraday volatility over the previous month. Intraday volatility is calculated using 5-minutes log return provided by TAQ.
Measures of volatility-of-volatility (VOV): Alternative definition	
EGARCH-VOV	The standard deviation of the daily realized stock volatility over the previous month, scaled by the average of daily volatility over the previous month. Each month for each stock, the daily realized volatility is estimated from the EGARCH (1,1) model using a rolling window of daily returns
IMPLIED-VOV	The standard deviation of the daily at-the-money implied volatility with 30 days of maturity over the previous month, scaled by the average of daily implied volatility over the previous month.
INTRADAY-VOV	The standard deviation of the daily intraday volatility over the previous month, scaled by the average of daily intraday volatility over the previous month. Intraday volatility is calculated using 5-minutes log return provided by TAQ.
Liquidity and demand pressure measures	
Ln(Amihud)	The natural logarithm of illiquidity, calculated as the average of the daily Amihud (2002) illiquidity measure over the previous month.
Option bid-ask spread	The ratio of the difference between the bid and ask quotes of option to the midpoint of the bid and ask quotes at the end of previous month.

Option demand pressure	(Option open interest / stock volume) $\times 10^3$. Option open interest is the total number of option contracts that are open at the end of the previous month. Stock volume is the stock trading volume over the previous month.
Ln (total size of all Calls)	The log of the total market value of the open interest of all call option in the previous month.
Volatility-related variables	
IVOL	Annualized stock return idiosyncratic volatility defined in Ang, Hodrick, Xing and Zhang (2006).
VOL_deviation	The log difference between the realized volatility and the Black-Scholes implied volatility for at-the-money options at the end of last month, as in Goyal and Saretto (2009). The realized volatility is the annualized standard deviation of stock returns estimated from daily data over the previous month.
VTS slope	Difference between the long-term and short-term volatility defined in Vasquez (2016).
Variance and Jump measures	
VRP	Variance risk premium is defined as the difference between the square root of realized variance estimated from intra-daily stock returns over the previous month and the square root of a model free estimate of the risk-neutral expected variance implied from stock options at the end of the month.
Jump_left/ Jump_right	Model-free left/right jump tail measure calculated by option prices, defined in Bolleslev and Todorov (2011).
Option-implied skewness and kurtosis	The risk-neutral skewness and kurtosis of stock returns, as in Bakshi, Kapadia, and Madan (2003), are inferred from a cross section of out of the money calls and puts at the beginning of the period.
Volatility spread	Spread of implied volatility between ATM call and put option.
Other uncertainty measures	
Analyst coverage	The number of analysts following the firm in the previous month.
Analyst dispersion	Standard deviation of analyst forecasts in the previous month scaled by the prior year-end stock price.
PIN	Probability of informed trading in Easley, Hvidkjaer, and O'hara (2002).

Table A1: Delta-Hedged Option Returns and Volatility-of-Volatility

(Alternative Definition)

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month end for both call options and put options. The calculation of the alternative VOV measures follows Baltussen, Van Bekkum, and Van Der Grient (2017). VOV is defined as the standard deviation of volatility scaled by the average of volatility in each month. IMPLIED-VOV is calculated using daily at-the-money implied volatility (delta=50) from the volatility surface file provided by OptionMetrics IvyDB database. EGARCH-VOV is calculated based on daily volatility estimated using EGARCH model. Each month and for each stock, the daily realized volatility is estimated from the EGARCH (1,1) model using a rolling window of daily returns over the past 12-month. INTADAY-VOV is calculated using daily intraday volatility calculated by five-minute log return provided by TAQ. 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-West (1987) t-statistics are reported in brackets.

Fama-Macbeth Regressions	Call Options: Delta-hedged gain till month end (Δ*S-C)				Put Options: Delta-hedged gain till month end (P - Δ*S)			
IMPLIED-VOV	-3.466***			-2.933***	-2.004***			-1.424***
	(-7.34)			(-5.49)	(-5.62)			(-3.68)
EGARCH-VOV		-1.705***		-1.254***		-1.374***		-1.058***
		(-11.64)		(-8.09)		(-11.20)		(-8.56)
INTRADAY-VOV			-1.725***	-1.220***			-1.418***	-1.099***
			(-7.42)	(-5.13)			(-7.47)	(-6.17)
Intercept	-0.475***	-0.482***	-0.265**	0.036	-0.279**	-0.355***	-0.107	0.096
	(-3.73)	(-4.12)	(-2.06)	(0.28)	(-2.35)	(-2.91)	(-0.88)	(0.82)
Adj. R^2	0.005***	0.003***	0.004***	0.011***	0.003***	0.003***	0.004***	0.009***

Table A2: Delta-Hedged Option Returns and Higher Order Moments of Volatility (Alternative Definition)

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month end for call options. The calculation of the alternative VOV measures follows Baltussen, Van Bekkum, and Van Der Grient (2017), which is defined as the standard deviation of volatility scaled by the average of volatility in each month. Skewness and kurtosis-of-volatility are defined as skewness and kurtosis of daily volatility level in each month. Implied volatility is the daily at-the-money implied volatility (delta=50) from the volatility surface file provided by OptionMetrics IvyDB database. EGARCH volatility is the daily volatility estimated using EGARCH model. In each month for each stock, the daily realized volatility is estimated from the EGARCH (1,1) model using a rolling window of daily returns over the past 12-month. Intraday volatility is calculated by five-minute log return provided by TAQ. 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-West (1987) t-statistics are reported in brackets.

Fama-Macbeth Regressions	Call Options Delta-hedged gain till maturity (Δ*S-C)		
	IMPLIED	EGARCH	INTRA-DAY
Volatility-of-volatility/average volatility	-3.383***	-1.029***	-2.124***
	(-6.94)	(-5.96)	(-7.37)
Skewness-of-volatility	-0.080***	-0.016	-0.100**
	(-3.98)	(-1.07)	(-2.67)
Kurtosis-of-volatility	0.011	-0.021***	0.046***
	(1.32)	(-4.11)	(4.44)
Intercept	-0.439***	-0.539***	-0.122
	(-3.20)	(-4.26)	(-1.01)
Adj. R^2	0.008	0.005	0.005