# Volatility Uncertainty and the Cross-Section of Option Returns*

[March 15 2018, Preliminary Draft]

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## Abstract

This paper studies the relation between the uncertainty of volatility, or 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 it is more difficult to hedge for these stock options.

* We thank Amit Goyal, Bing Han, Inmoo Lee, and seminar participants at Chinese University of Hong Kong, Erasmus University Rotterdam, Korea Advanced Institute of Science and Technology, and University of Hong Kong. All errors are our own.

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## Abstract

This paper studies the relation between the uncertainty of volatility, or 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 it is more difficult to hedge for these stock options.



*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 have important implications for explaining the phenomena in the financial markets, such as volatility smile and skew, and for pricing derivatives more accurately, compared with the models with constant volatility. While there is a consensus that stochastic volatility is both important for financial econometrics and asset pricing[3], an equally important but less examined aspect is how the uncertainty in time-varying volatility affects cross sectional asset return.

In this paper, we focus on equity option market, which has become larger and more liquid in recent years, and study whether uncertainty (volatility) 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) 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 entire 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 this risk associated to volatility uncertainty, risk-averse option writers charge a higher option implied volatility as a compensation 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 construct the delta-hedged option portfolio, in which the portfolio returns are mainly affected by volatility changes and the stock price movements are removed with a daily delta hedge. We formally test this hypothesis by studying

[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 et al. (2003)).

[3] 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 (2012). 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.

the predictability of volatility uncertainty on future delta-hedged equity option returns. We use three daily measures of volatility for each stock: (1) volatility estimated from an EGARCH (1,1) model using rolling 252 trading days; (2) implied volatility from 30 day to maturity options; (3) intraday realized volatility from 5-minute stock returns. We compute volatility of volatility (VOV) as the standard deviation of the percentage change in daily volatility over the previous month. The 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. The three measures of VOV have low time series average of cross-sectional correlations, ranging from 7% to 12%. We find that all of the three VOV measures predict future option returns. Fama-French regressions results reveal that each VOV estimate significantly predicts 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. The magnitude of the coefficients and the significance level are similar for both calls and puts. Joint regressions of the three VOV measures are statistically significant, which confirms the distinctive information content of these three measures.

These 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 volatility term structure in Vasquez (2017). The results are robust after controlling for volatility risk premium, implied jump risk measures (Bolleslev and Todorov (2011)), implied skewness (Bakshi, Kapadia and Madan (2003)), volatility spread (Yan (2011)), liquidity and demand pressure measures. The VOV effect cannot be explained by alternative firm-level uncertainty measures such as analyst coverage and analyst dispersion and firm characteristics that have been documented to as strong option return predictors in Cao et al. (2017). We also explore the relation between option returns and higher order moments of volatility. We find that the skewness of volatility and the kurtosis of volatility significantly predict future option returns. After controlling skewness and kurtosis of volatility, the three VOV measures are still statistically significant, suggesting that VOV captures information that skewness and kurtosis of volatility do not contain.

To investigate the economic magnitude of the predictability, we form quintile portfolios of delta-neutral covered call writing strategy sorted on VOV. The stock position is rebalanced at daily to remove the exposure of the portfolio to stock price movements. 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 measures of VOV ranging from 0.52% to 1.04% per month. The results are robust to different weighting schemes. To comprehensively capture the information 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 generates a monthly return spread that ranges between 0.92% and 1.06%. The combined VOV return spread and its t-statistic are higher than the ones generated by any of 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 the extent to which the VOV effect is alleviated by news arrival, e.g. the earning announcements, and reflects biased expectation by the option arbitrageurs. We find that the return spread is smaller around earnings announcement days, suggesting that the VOV effect cannot be explained by the explanation that biased expectation is corrected by the firm-specific information releases. Second, we find that volatility of idiosyncratic volatility drives most of the predictability, rather than the volatility of systematic volatility. The results stay robust when we decompose VOV into its systematic and idiosyncratic components in two other ways. The results show that the VOV effect is difficult to be reconciled with classic risk-based theories such as the arbitrage pricing model or ICAPM model, while it is more consistent with the explanation that option with high volatility of idiosyncratic volatility is more difficult to hedge for the market makers. They charge a high price for these options, which leads to low return in the future. Third, we decompose the VOV into volatility of positive percentage change of volatility (VOV+) and volatility of negative percentage change of volatility (VOV-). For implied VOV, VOV+ has a larger impact on future option return than VOV-. We explain that option writers dislike VOV+ more than VOV-, because options with historically high VOV+ might have future high VOV+ and cause potential loss for the option writers.

Our paper contributes to several streams of literature. First, this paper contributes to the literature on option return predictability. Previous studies find that high deviation between implied volatility and realized volatility (Goyal and Sarreto (2009)), high idiosyncratic volatility (Cao and Han (2013)), high skewness (Bali and Murray (2013) and Boyer and Vorkink (2014)), and volatility term structure (Vasquez (2017)) are related to lower delta-hedged equity option returns. From the perspective of option market microstructure, Christoffersen, Goyenko, Jacobs, and Karoui (2018) find a positive illiquidity premium in daily option returns. Muravyev (2016) documents that option market order-flow imbalance significantly predicts daily option returns. Some recent studies also examine whether stock characteristics and firm fundamentals can predict option returns. For instance, Cao, Han, Tong, and Zhan (2017) find that 8 out of 12 well known stock market anomalies have significant predictability in future delta-hedged option returns. Vasquez and Xiao (2017) examine the relation between firm leverage, credit risk, and delta-hedged option return from a theoretical point of view using capital structure model of a firm. Another recent study by Cao, Jin, Pearson, and Tang (2017) find that equity options with associated credit default swaps trading experience lower delta-hedged gains. Different from the previous literature, our paper uses distributional characteristics of volatility movements to predict option return after adjusting for exposures to the underlying stocks.

Second, our paper documents an important but underexplored aspect of volatility uncertainty, that is, its impact on the equity option market. Baltussen, Van Bekkum, and Van Der Grient (2017) find that high VOV stocks have lower expected stock returns compared to low VOV stocks. In the study, they argue that the negative VOV effect can be reconciled with models that assume difference in uncertainty preferences of investors. Other studies also show that the aggregate VOV, as a systematic risk factor, explains cross sectional variations of stock returns (Chen, Chordia, Chung, and Lin (2017) and Hollstein and Prokopczuk (2017)) and hedge fund returns (Agarwal, Arisoy, and Naik (2017)). The role of volatility of volatility is less explored in the option markets. For index option, Huang, Schlag, Shaliastovich, and Thimme (2018) show that time-varying volatility of volatility affects both the cross-section and the time-series of index and VIX option returns. We contribute to this literature by focusing on the effect of distribution characteristics of volatility change on future equity option return at the stock level. 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).

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

## 2. Data and Variables

### *2.1. Data and sample coverage*

The option data on individual stocks is 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 various greeks such as delta, gamma and vega from January 1996 to April 2016. Implied volatility and greeks are calculated by OptionMetrics using binomial trees in 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 return is 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. The options in our sample are therefore very close to European style options. Third, we exclude all options that violate the no arbitrage conditions. Fourth, we only keep options with moneyness higher than 0.8 and lower than 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 with more than one month to expire. We drop options whose maturity is different from the majority of options.[4]

Our final sample contains 327,016 option-month observations for calls and 305,710 option-month observations for puts. Table 1 shows 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 standard deviation of 5%. The time to maturity ranges from 47 to 50 days. The

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

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 correlated with 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 of 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+ $\tau$ 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 $r$ 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 $t_n$. 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 $\Delta_{C,t_n}$ 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 $\alpha_n$ 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 return of the portfolio comparable across stocks with different stock and option prices, we follow Cao and Han (2013) who scale the delta-hedged gain by ($\Delta_t * S_t - C_t$) for calls and by ($P_t - \Delta_t * S_t$) for puts, which is the negative value of the initial investment.[5]

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 return 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 similar.

[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 estimated using the following EGARCH (1,1) model with daily stock returns[6]:

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

where $r_t$ is the stock return, $\sigma_t$ 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 current month).[7] It generates a series of time-varying volatility level for each day in the estimation window. The maximum number of iterations is 500 for the maximum likelihood estimation and over 96% of EGARCH regressions in our sample successfully converge.

The second measure of daily volatility is extracted from the volatility surface provided by OptionMetrics. The advantage of using the volatility surface is that the daily implied volatility has constant maturity and delta. We use the at-the-money (delta=0.5) implied volatility of the

[5] We obtain similar results when we scale by the initial price of the underlying stock or by the initial price of the option.
[6] 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.
[7] 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.

call options with 30 days of maturity. Then we use the daily implied volatility within a given month to calculate the monthly VOV, which is described in the following.[8]

The third measure of daily volatility level 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.

After obtaining these 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 $\sigma_t$ is volatility at day t and $\sigma_{t-1}$ is volatility at day t-1. Figure 1 shows that 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 physical measure of standard deviation in our analyses to estimate the volatility of volatility.

[Insert Figure 1 about here]

The monthly VOV measures are then calculated as the standard deviation of the daily percentage change in volatility within each month. This definition of VOV is slightly 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. In Panel G of Table 2, we show that the correlations among these two definitions of VOV are around 0.7. The main reason that we define our VOV measure based on "return of volatility" is that the definition is in line with the *VVIX index* provided by CBOE. From the CBOE website, *VVIX* is the implied volatility of VIX futures return. If we consider volatility as an asset, similar to a stock, then the volatility of this asset is defined based on its return. We refer to this definition as "Definition 1" for main analysis of this paper. For robustness, we also use the measure from Baltussen et al. (2017), which is referred as "Definition 2". Since implied volatility is at the annual level, we also annualize the other two volatility measures to calculate the VOV measures.

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

[Insert Table 2 about here]

Table 2 reports summary statistics for the three volatility measures along with 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 respectively. The level of the volatility of 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 volatility calculated from high frequency stock returns is more volatile than volatility calculated form low frequency (daily) stock returns. The skewnesses of percentage change in volatility (SoV) are all positive for the three volatility measures.

Summary statistics for VOV measures defined in Baltussen et al. (2017) show similar patterns, as reported in Panel D-F of Table 2. We report the time series averages of the cross-sectional correlations of the six VOV measures (three under our main specifications and three according to Baltussen et al. (2017)). Panel G in Table 2 shows low cross-sectional correlations among different VoV measures. For example, the correlation between IMPLIED-VOV and EGARCH-VOV is 0.07. Low correlations among different VOV measures suggest that the three measures may contain distinct information. More specifically, option implied volatility is forward looking as an estimate of the volatility in the future 30 days. Since option prices are usually quoted in implied volatility, IMPLIED-VOV reflects the movement of historical option prices, which might affect option trader's expectation more than the other two realized VOV measures. EGARCH measure uses the daily stock return to estimate the daily conditional volatility. Intra-day measure utilizes 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 the 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 sorting on the three measures of VOV (DEF 1). 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 portfolio strategies based on the return to delta-neutral call writing.

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

We first study whether and how VOV measures predict future delta-hedged option gains in the cross section using monthly Fama-MacBeth regressions. The dependent variable in month $t$ regression is the delta-hedged option gain until month end scaled by the initial investment of the option portfolio, that is, $\prod(t, t+\tau)/(\Delta_t * S_t - C_t)$ for calls and $\prod(t, t+\tau)/(P_t(P_t - \Delta_t * S_t)$ for puts. To avoid the impact of outliers on regression analyses, we winsorize all the explanatory variables each month 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 until month end on VOV measures for call and put options. VOV is defined as the standard deviation of percentage change of volatility ($\Delta\sigma/\sigma$) in each month (DEF. 1). The three VOV measures are described in Section 2. The coefficients of the three VOV measures are significantly negative for both call and put options. The results confirms 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. For example, the estimated coefficient for IMPLIED–VOV is -3.003 with a t-statistic of -6.30. The t-statistics of the coefficients of EGARCH-VOV and INTRADAY-VOV are -10.08 and -6.53, respectively. We further conduct a Fama-MacBeth regression with the three VOV and all of them are statistically significant. Moreover, the adjusted $R^2$ of the joint regression is higher than the adjusted $R^2$ of all univariate regressions, suggesting that the three VOV measures together explain a larger portion of cross sectional variation in option return. The results are similar for call and put options.

[Insert Table 3 about here]

We provide regression results for the three VOV measures using definition in Baltussen et al. (2017) (DEF.2) in Panel B of Table 3. The three VOV measures are significantly negative in univariate regressions and in the joint regression for both call and put options. The t statistics of the coefficients are slightly higher than those in Panel A of Table 3. Hence, the results are robust to different definition of VOV.

We also check the robustness of the joint regression of the three VOV measures using alternative measures of delta-hedged call option returns in Panel C of Table 3. The dependent variables are delta-hedged gain till month-end scaled by stock price in Model (1), delta-hedged gain till month-end scaled by stock price in Model (2), delta-hedged gain till maturity scaled by ($\Delta$*S - C) in Model (3) and delta-hedged gain till week end scaled by ($\Delta$*S - C) in Model (4). The results suggest that the predictive power of the three VOV measures is robust whether the delta-hedged option return is held until week end, month end or maturity. The effect is also robust whether the delta-hedged gain is scaled by initial investment or by stock price.

### *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. All results of put options are consistent and 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. To control for these possibilities, we consider the following three volatility-related variables in Panel A of Table 4. 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 return 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 to be 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 return is consistent with the mean reversion of volatility and 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) find that VTS slope is a strong predictor variable for the future straddle return of the 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.

After controlling for other known measures related volatility, the three VOV variables remain to be significant in all regressions. The economic significance decrease a bit, but still remains to be large. Overall, the result suggests that our documented impact of VOV on the cross-sectional delta-hedged option returns cannot be explained by the 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 may come from the correlation between VOV and variance risk premium. Previous studies (e.g., Bakshi and Kapadia (2003); Bakshi, Kapadia, and Madan (2003)) show that delta-hedged option gains are closely related to the variance risk premium. Tauchen, Bollerslev and Zhou (2009) show that variance risk premium at the index level, defined as the difference between option implied variance and realized variance, is proportional to the time varying volatility-of-volatility in an extended long-run risk model. Consequently, VOV and future delta-hedged option return 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 (2008); 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 then examine whether our results can be explained by the correlations of individual stock variance risk premium and VOV measures.

We now further control for the one-month individual stock variance risk premium (VRP) in our Fama-MacBeth regressions. Following Jiang and Tian (2005), and Bollerslev, Tauchen, and Zhou (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 empirical counterpart is proxied by realized return variance computed from high-frequency return data over the given month.

Table 4 Panel B reports a significantly positive coefficient for individual stock variance risk premium in all regressions, 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 is not likely to 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 the jump risk when they write options. The negative VOV effect might potentially reflects a compensation for the jump risk. Firms with higher uncertainty in volatility may experience sudden stock price jump or drop. To address the concern that the effect of VOV can be explained by the jump risk of the individual stocks, we consider three sets of jump measures as control variables in Panel C of Table 4. The first set contains Jump_left and Jump_right, defined as the model-free left/right jump tail measures calculated from option prices according to Bolleslev and Todorov (2011). The second jump risk variable is the implied skewness, which is the risk-neutral skewness of stock returns inferred from a portfolio of options across different strike prices, following Bakshi et al. (2003). Note that the calculation of implied skewness requires at least three out-of-the-money call options and three out-of-the-money put options, which substantially reduces the sample to about 1/3 of the original sample. Jump risk manifests itself in implied skewness when it deviates from zero. 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). The coefficients of Jump_left and Jump_right are both statistically negative, indicating that higher jump risk predicts lower delta-hedged option return, irrespective of the direction of the jump. Implied skewness has significant coefficients in all regressions with negative signs. Volatility spread is also a strong predictor of delta-hedged option return. The magnitude and t-statistics of the VOV are smaller after controlling variables related to jump risks, but the coefficients remain economically large and significant.

*3.2.4. Control for liquidity and option demand pressure*

Christoffersen et al. (2018) document significant illiquidity premia in equity option markets. The high VOV stock options could be those with high liquidity and hence have low expected returns. Bollen and Whaley (2004) and Garleanu, Pedersen, and Poteshman (2009) argue that demand pressure plays an important role in the pricing of options. High VOV stock options could have higher demand pressure than the low VOV stock options and the high VOV stock options are relatively more expensive with lower future return. In Table 5, we report the Fama-Macbeth regression results of the delta-hedged option return on VOV measures after controlling for liquidity and demand pressure measures. We consider both stock and option illiquidity: Ln (Amihud) and option bid-ask spread. Ln (Amihud) is the natural logarithm of illiquidity, 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.[9]

We confirm the results in Christoffersen et al. (2018) that the higher the stock illiquidity, the lower the expected option returns. The stock liquidity measure and two option demand pressure measures are also statistically significant in all regressions. The three VOV variables

[9] 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.

remain significant after controlling for the liquidity and demand pressure measures with t-statistics -3.63 to -6.95, suggesting that liquidity and demand pressure cannot fully explain the VOV effect.

[Insert Table 5 about here]

*3.2.5. Control for stock information uncertainty and asymmetry*

VOV measures the uncertainty of the firm-level volatility, which could be potentially correlated with other uncertainty measures about the firm fundamentals and information asymmetry. In Table 6, we control for two other types of information uncertainty and one measure of information asymmetry that might affect delta-hedged option returns. Previous literature finds that information risk affects expected stock return. Diether, Malloy, and Scherbina (2002) and Zhang (2006) find that lower analyst coverage is associated with higher expected stock return. 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 the information uncertainty, asymmetry and delta-hedged option return, we consider analyst coverage, analyst dispersion and PIN as control variables for VOV.

Table 6 shows that the information uncertainty and asymmetry measures are significant in the Fama-Macbeth cross-sectional regressions. Consistent with the channel of information risk, the result suggests that the lower the analysis coverage and the higher the dispersion, the lower the future delta-hedged option return. 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 other uncertainty measures.

[Insert Table 6 about here]

*3.2.6. Control for firm characteristics*

Cao et al. (2017) find that many stock characteristics and firm fundamentals can predict the cross-section of delta-hedged equity option returns, although these variables do not generate significant abnormal profits over the same sample period in the stock market. In Table 7, 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.

We find that all firm characteristics are highly significant in the Fama-Macbeth cross-sectional regressions. The strongest predictor among these characteristics is profitability, with t-statistics ranging from 10.23 to 12.42. After controlling for the 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 the firm characteristics.

[Insert Table 7 about here]

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, other uncertainty variables, and stock characteristics.

*3.3. Portfolio analysis*

The patterns of VOV and future delta-hedged option return found in the Fama-Macbeth regressions suggest a set of profitable trading strategies in the equity option market. In this subsection, we explore portfolio sorting 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.[10] The position is held for a month with updating the delta-hedge at a daily basis. For each stock and in each month, we compound the daily returns of the rebalanced delta-hedged call-option positions over the month to obtain the monthly return. Table 8 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 8 about here]

*3.3.1. Single portfolio sorts on VOV measures*

At the end of each month and for each stock characteristic, we sort all optionable stocks into five quintiles and then compare the portfolios of delta-neutral call writing on the stocks belonging to the top quintile versus the bottom quintile.[11] We use two weighting schemes in calculating the average return of a portfolio of delta-neutral call writing strategy: equal weight (EW), weight by the market value of the option open interests at the beginning of the holding period (OW). Table 8 Panel B reports the average return for each quintile portfolio and the return spread of the top and bottom quintile portfolio. The associated Newey-West (1987) t-statistics are reported in parentheses.

The portfolio returns increase monotonically for all three VOV measures and for both EW and OW weightings. For the EW weighting scheme, the (5-1) spread portfolios formed by sorting on IMPLIED-VOV, EGARCH-VOV, and INTRADAY-VOV have monthly returns of 0.52% with t-statistic of 10.46, 0.88% with t-statistics of 13.77 and 0.47% with t-statistics of 5.28, respectively. The OW weighting scheme generates higher return spread for the strategies sorting on the three VOV measures, suggesting that the VOV effects are not driven by illiquid stock options. The return spreads are 0.57%, 1.04% and 0.54% per month with t-statistics of 9.95, 13.38 and 6.35, respectively.

Apart from sorting the portfolios on the three VOV measures separately, we also consider sorting the portfolios on the combination of the three VOV measures. Our method is similar to

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

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

Stambaugh, Yu, and Yuan (2015) and Cao and Han (2016) in 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 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 then rank the stock option portfolios by its composite ranking into five quintiles. The result of the combination strategy is reported in the last four rows in Table 8 Panel B. The magnitudes of both return spread and the t-statistics increase compared with those based on single 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 returns to delta-neutral call writing and 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 analysis of Fama-Macbeth regression and portfolio sorting establishes a robust negative relation between VOV and the expected delta-hedged option return. It is possible that the trading strategy is exposed to some priced risk factors and the exposures could potentially explain the return spread of the VOV strategies. We therefore examine whether the return of our option strategies can be explained by a set of existing common risk factors in the literature. The risk factors include 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 several volatility factors including the zero-beta straddle return of the S&P 500 Index option (Coval and Shumway (2001)), the change in the Chicago Board Options Exchange Market Volatility Index (ΔVIX, Ang et al. (2006)). We regress the time series of equal-weighted monthly returns of our option portfolio strategies on the risk factors and examine whether the intercept terms are significantly different from zero.

Table 8 Panel C shows that none of these common risk factors can explain the profits of our option portfolio strategies based on the three VOV variables and the combined VOV. After controlling for these risk factors, all of the alphas remain highly significant and are similar in magnitudes as the raw returns. Thus, our option strategies based on VOV and combined VOV generate abnormal profits that are largely independent of the common risk factors in the stock market and various volatility risk factors.

## 4. Further Discussions

### *4.1. The impact of VOV and 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 expectation.

To examine the extent to which the VOV effect takes place during the earning announcements and reflects biased expectation, we take two approaches. First, we examine the VOV effect for firm-months with and without earning announcements, respectively. We then form quintile portfolios based on the three measures of VOV within each subset, and report the 5-1 return spread across subsets in Table 9. The return is calculated from the daily rebalanced and compounded return of the delta-neutral call writing strategy. The second column reports the average return spread of all stocks and months. The third column reports the average return spread in the months without earning announcement. The fourth column reports the average return spread in the months with earning announcements. The return spread decreases to about 34, 20, and 12 basis points for IMPLIED-VOV, EGARCH-VOV, and INTRADAY-VOV, for the subset of stocks with earning announcements. This result suggests that the VOV effect is even smaller in the months with earnings announcements.

Furthermore, we analyze the VOV effect in the months with earning events. We split the months with earning announcements into two parts: over the [-1, 1] event window and over the other days in a month. The fifth column of Table 9 reports the average return spread over the [-1,1] event window in the months with earning announcement and the sixth column reports the average return spread over the other days in that 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. Hence, the VOV effect is mostly present in the months and days without earning announcement. These results indicate that the news about earning announcements does not tend to drive the VOV effect in the equity option market. The VOV effect is unlikely to be explained as biased expectation because the VOV return spread is not distinguishable for the full month and the days in a month excluding earning announcements.

[Insert Table 9 about here]

*4.2. 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, other dimensions of volatility change may also be considered as important to option market participants. In this subsection, we expand our analysis to two additional important characteristics of volatility change: skewness and kurtosis. For each of the three volatility measures, we calculate the skewness and kurtosis of percentage change in volatility month for each stock each month. We then run Fama-Macbeth regression and examine the impact of volatility, skewness, and kurtosis of volatility change 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.

The average coefficients, t-statistics and adjusted R-squared are reported in Table 10, with each column reporting one method to estimate volatility. 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 in predicting future option returns. However, the signs are not consistent across the measures based on implied volatility, EGARCH volatility and intraday volatility. The three VOV measures remain significant after controlling for skewness and kurtosis of volatility change. Overall, we find higher order moments of volatility such as skewness and kurtosis cannot explain the predictability of VOV for future delta-hedged option returns.

[Insert Table 10 about here]

*4.3. Systematic volatility and idiosyncratic volatility*

A natural question would be the uncertainty about whether the movement of systematic or idiosyncratic volatility is more of a concern to option market participants. In this subsection, we decompose EGARCH volatility into a systematic component and an idiosyncratic one. [12] Then we explore whether the predictability of VOV on delta-hedged option return is driven by uncertainty in systematic volatility or uncertainty in idiosyncratic volatility. We argue that stock options with high uncertainty in idiosyncratic volatility is more difficult to hedge than those with high uncertainty in systematic volatility. The movement of systematic volatility could possibly be hedged by trading VIX futures or index options, while it is difficult to find a financial product that is able to hedge the firm-specific volatility movement. By considering the two components separately, we examine the role of difficult-to-hedge in explaining the VOV effect.

For each stock, we first estimate the daily total volatility $\sigma_t$ (Total Vol) with a EGARCH (1,1) model using a rolling window of 252 trading days. Then we estimate daily idiosyncratic volatility (Idio Vol) $\sigma_{\varepsilon,t}$ using EGARCH (1,1) model with Fama-French 3-factor in the return equation of the model.[14] Daily systematic volatility (Sys Vol) is then defined as $\sqrt{\sigma_t^2 - \sigma_{\varepsilon,t}^2}$. We then calculate Vol of Idio Vol as the standard deviation of percentage change in $\sigma_{\varepsilon,t}$ in the past month and Vol of Sys Vol as the standard deviation of percentage change in daily systematic volatility in the past month.

We then run the Fama-Macbeth cross sectional regression of delta-hedged option return on Vol of Total Vol, Vol of Idio Vol and Vol of Sys Vol. The average coefficients, t-statistics and adjusted $R^2$ are reported in Table 11. The coefficients of Vol of Idio Vol and Vol of Sys vol are both statistically negative in the univariate and joint regressions. The coefficients and t-statistics of Vol of Idio Vol are larger in magnitude than those of Vol of Sys vol, suggesting that Vol of Idio Vol is a more important than Vol of Sys Vol in determining expected delta-hedged option returns. The evidence is consistent with the explanation that option sellers demand a high price for high VOV options because they are difficult to hedge.

[12] 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 daily frequency for the other two volatility measures.

[14] 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.

[Insert Table 11 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 more consistent with risk-based theory or market friction, we decompose the daily change of implied volatility and EGARCH volatility into exposure to the percentage change in market volatility and an idiosyncratic component.

To decompose the daily change of implied volatility, we use implied volatility of each stock as $\sigma_t$ and VIX index as $\sigma_{mt}$. 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 ($\sigma_t$ ) and for S&P 500 index ($\sigma_{mt}$ ). 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 percentage change of $\sigma_{mt}$ (Beta to (%Δ in MKT Vol)). RMSE of $\hat{\epsilon_t}$ is defined as the idiosyncratic volatility of change in volatility (Vol of (idio %Δ in Vol)). The results of Fama-Macbeth regression are reported in Table 12. Beta to (%Δ in MKT Vol) and Vol of (idio %Δ in Vol) are both significant determinants of expected delta-hedged option return, while the effect of Vol of (idio %Δ in Vol) is much larger than that of Beta to (%Δ in MKT Vol) in terms of both coefficients, t-statistics and R squared. Hence, both components predict delta-hedged option return, while the idiosyncratic volatility of the volatility change plays a more important role. However, the positive sign of the systematic exposure is not consistent with ICAPM for both decompositions using implied and EGARCH volatility, indicating that risk-based theory unlikely explains the VOV effect.

[Insert Table 12 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 ($\sigma_t$ ) and for S&P 500 index ($\sigma_{mt}$ ). For each month and each stock, we run the following regression with monthly data using the observations in 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 $\sigma_{mt}$ (Beta to MKT-VOV). RMSE of $\widehat{\epsilon_t}$ is defined as the residual volatility of change in volatility (Residual_VOV). The average coefficients, t-statistics and adjusted R squared of Fama-Macbeth regression on the two components of EGARCH - VOV are reported in Table 13. The results are similar to those in Table 12 that idiosyncratic component drives the VOV effect. Overall, the three decomposition methods show that the VOV effect cannot be explained by risk-based theories. It is more consistent with the conjecture that option writers change a high price for those stock options that are difficult to hedge.

[Insert Table 13 about here]

*4.6. Volatility of positive and negative percentage change of volatility*

If VOV is considered as a measure of how difficult it is to hedge the stock option position for the option writer, volatility of positive volatility change and volatility of negative volatility change might have different effect on traders' evaluation of the option price. For the option writers, they are more concerned with positive volatility change than negative volatility change because the former leads to potential loss. Hence, the effect of volatility of positive volatility change might be larger in magnitude than the effect of volatility of negative volatility change in predicting future option returns.

To test this hypothesis, we calculate VOV+ as the volatility of positive volatility percentage change in the past month, VOV- as the volatility of negative volatility percentage change in the past month. In Table 14, we report the Fama-Macbeth regression results for different specifications. Panel A and B show univariate regression results of VOV+ and VOV- respectively. The results confirm the dominating effect of VOV+ calculated based on implied volatility. Our hypothesis is confirmed by the fact that the coefficient of IMPLIED VOV+ is highly significant with t-statistics -6.78, while the coefficient of IMPLIED VOV- is not statistically significant. However, VOV+ and VOV- based on EGARCH and INTRADAY volatility both significantly predict future delta-hedged option return with similar magnitude of t-statistics, suggesting that evaluation decision of option writers depends more on IMPLIED-VOV than EGARCH-VOV and INTRADAY-VOV.

First, we discuss the explanation of the asymmetric effect of IMPLIED-VOV+ and IMPLIED-VOV-. Lakonishok, Lee, Pearson, and Poteshman (2006) and Nicolae, Pedersen, and Poteshman (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 option. For option writers, hedging is necessary because the risk of naked option writing is unlimited and brokers usually require covered positions. These end users are more concerned 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; 2) high IMPLIED-VOV+ options may be more likely to experience large volatility increase in the future, leading to higher potential loss. Consequently, they charge a higher price for high VOV+ options, which causes low return in the future. Option writers are less concerned about high VOV- options. Although they are still difficult to hedge, they are likely to experience volatility decreases in the future, leading to potential gain. Moreover, option buyers are not willing to buy an expensive option with high VOV- due to the potential 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.

Second, we provide an explanation about why the asymmetric effect is not consistent for IMPLIED-, EGARCH-, and INTRADAY-VOV. 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 and INTRADAY – VOV are too costly for them to pay attention. However, market makers utilize different sorts of 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 two realized volatility measures, they charge a premium for options with either high VOV+, or high VOV-, leading to low future option returns.

We further define signed jump of variance (JOV) as the square of VOV+ minus the square of VOV-, divided by VOV. In Table 14 Panel C, we show bivariate regression results of VOV+ and VOV-. We find that, for the three volatility measures, VOV+ and VOV- do not subsume information of each other. In the bivariate regressions, both VOV+ and VOV- are statistically significant and the adjusted $R^2$ increases compared with that in the univariate regressions. In particular, the coefficient of IMPLIED-VOV- becomes significantly positive. In Panel D, we show bivariate regression results of VOV and JOV. JOV provides information in predicting future delta-hedged option return in addition to the total 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 JOVs, suggesting that information about implied volatility affect option writers' valuation decision more than information about EGARCH and INTRADAY volatility. This is consistent with the fact that end user are option writers and less sophisticated. The effect of INTRADAY-JOV is significantly positive, compared with the negative effect of IMPLIED and EGARCH-JOV, suggesting that information about INTRADAY volatility affect option buyers' valuation decision more than information about EGARCH and IMPLIED volatility. This is consistent with the fact that market makers are net option buyers and they have more resources and access to the costly information.

[Insert Table 14 about here]

## 5. Conclusion

This paper documents a robust negative relationship between volatility-of-volatility and future delta-hedged option returns. Our results show that option writers tend to charge a higher premium for equity options whose volatility is difficult to forecast and which are difficult to hedge. We measure the daily volatility in three ways: implied volatility from the volatility surface, 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: EGARCH–VOV, IMPLIED–VOV and INTADAY–VOV. The three VOV measures have lower cross-sectional correlations, suggesting that they contain information of VOV from different perspectives.

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 other firm-level uncertainty variables and stock characteristics which are documented to predict option return. Motivated by the regression results, we construct a set of tradable option portfolio strategies based on delta-neutral call writing and sorted by the three VOV measures. These option portfolio strategies deliver positive average returns that remain approximately the same magnitudes after controlling for common risk factors from the stock market and various volatility risk factors.

To understand the sources of the VOV predictability, we explore several potential explanations. First, we find that the return spread does not come from days around earnings announcements, suggesting that the VOV effect cannot be explained by the behavioral explanation that biased expectation gets corrected by the firm-specific information releases. Second, we find that the most of the predictability is driven by the idiosyncratic components of VOV in several dimensions, rather than by any systematic components. 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, while it is more consistent with the explanation that option with high volatility of idiosyncratic volatility is more difficult to hedge for the market makers. Third, we decompose the VOV into volatility of positive percentage change of volatility (VOV+) and volatility of negative percentage change of volatility (VOV-). For implied VOV, VOV+ has a much larger impact on future option return than VOV-, while the effects of VOV+ and VOV- is symmetric for two realized volatility measures. We explain that option writers dislike VOV+ more than VOV- for implied volatility; however, for two realized volatility measures, market makers charge a premium for options with either high VOV+, or high VOV-.

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## Appendix: Variable Definitions

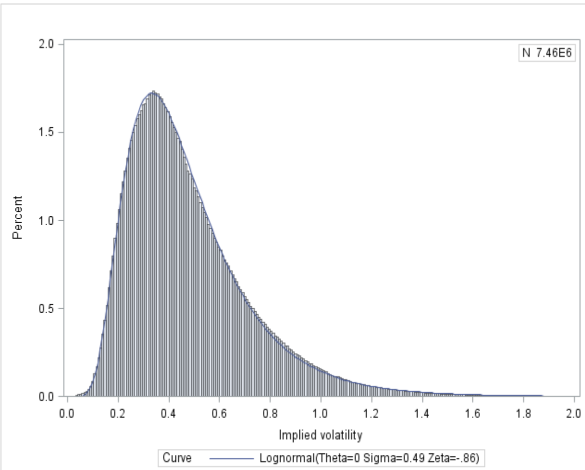
| | |
|---|---|
| *Measures of volatility of volatility (VOV): Definition 1* | |
| EGARCH – VOV | The standard deviation of the percent change in daily realized stock volatility over the previous month. Each month for each stock, the daily realized volatility is estimated from the EGARCH (1,1) model 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): Definition 2* | |
| 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). |

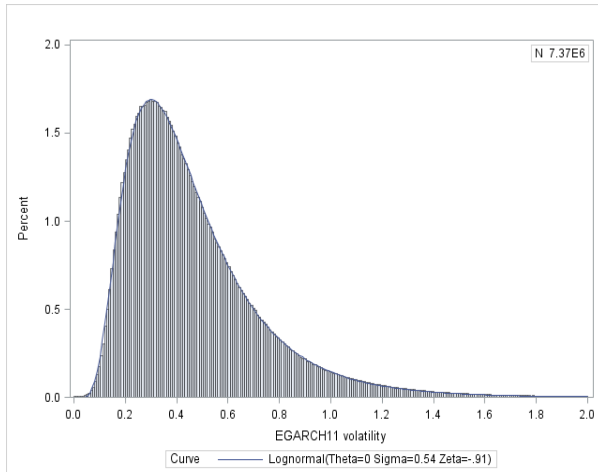
**Figure 1. Distribution of daily volatility level and the percentage change of volatility (Δσ/σ)**

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.

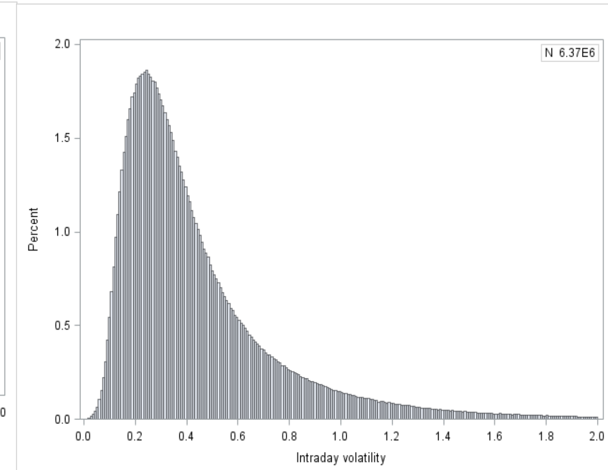
(a) Implied Vol



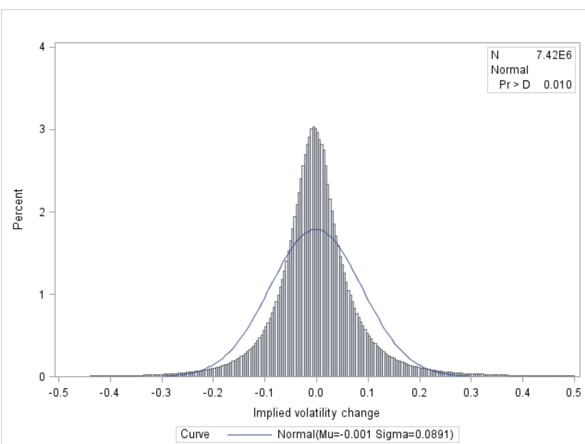

(b) EGARCH Vol



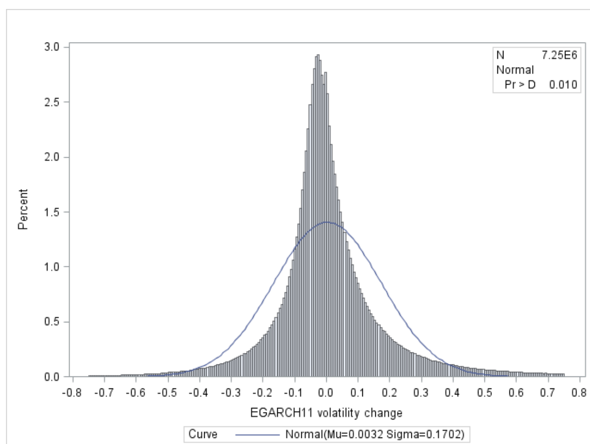

(c) Intraday Vol



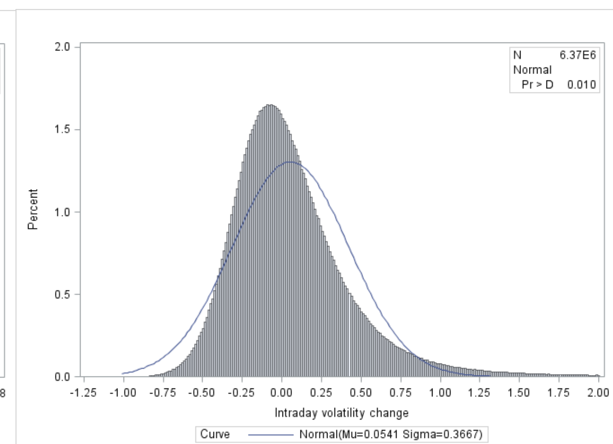

(d) Change of Implied Vol




(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. In Panel A (Panel B), call (put) option delta-hedged gain is the change over the next month or until option maturity in the value of a portfolio consisting of one contract of long call (put) position and a proper amount of the underlying stock, re-hedged daily so that the portfolio is not sensitive to stock price movement. The call option delta-hedged gain is scaled by (Δ*S-C), where Δ is the Black-Scholes option delta, S is the underlying stock price, and C is the price of call option. The put option delta-hedged gain is scaled by (P-Δ*S), where P is the price of put option. Moneyness is the ratio of stock price 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, Panel B and Panel C, VOV, SOV and KOV are volatility, skewness and kurtosis of percentage change of volatility ($\Delta\sigma/\sigma$) in each month, which is considered as the first definition of volatility moments. In Panel D, Panel E and Panel F, VOV is defined as standard deviation of volatility scaled by the mean of volatility in the previous month. SOV and KOV in these three panels are defined and skewness and kurtosis of volatility in the previous month, which is referred as the second definition of volatility moments. Under each definition, we calculate volatility moments using three measures of volatility. Panel A and D are based on the daily at-the-money implied volatility (delta=50) from the volatility surface file provided by OptionMetrics IvyDB database. Panel B and E are calculated based on daily volatility estimated using 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 and F are based on the daily intraday volatility calculated by five-minute log return 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 (DEF.1) | | | | | | | |
| Vol level $\sigma$ | 0.48 | 0.25 | 0.23 | 0.30 | 0.43 | 0.60 | 0.80 |
| Vol change ($\Delta\sigma/\sigma$) | 0.00 | 0.02 | -0.02 | -0.01 | 0.00 | 0.01 | 0.02 |
| 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 (DEF.1) | | | | | | | |
| Vol level $\sigma$ | 0.47 | 0.30 | 0.20 | 0.28 | 0.40 | 0.58 | 0.82 |
| Vol change ($\Delta\sigma/\sigma$) | 0.03 | 0.08 | -0.02 | 0.00 | 0.01 | 0.03 | 0.08 |
| 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 (DEF.1)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Vol level $\sigma$ | 0.45 | 0.34 | 0.16 | 0.23 | 0.35 | 0.55 | 0.86 |
| Vol change ($\Delta\sigma/\sigma$) | 0.07 | 0.08 | -0.01 | 0.02 | 0.06 | 0.10 | 0.16 |
| 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: Based on Daily Option Implied Volatility, 324, 765 observations (DEF.2)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| VOV (Vol of $\sigma$) / $\bar{\sigma}$ | 0.10 | 0.07 | 0.04 | 0.06 | 0.08 | 0.11 | 0.16 |
| SOV (Skew of $\sigma$) | 0.22 | 0.96 | -0.84 | -0.29 | 0.21 | 0.73 | 1.35 |
| KOV (Kurt of $\sigma$) | 1.34 | 2.64 | -0.84 | -0.34 | 0.51 | 2.03 | 4.57 |

Panel E: Based on EGARCH (1,1) Daily Return Volatility, 304,884 observations (DEF.2)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| VOV (Vol of $\sigma$) / $\bar{\sigma}$ | 0.15 | 0.16 | 0.05 | 0.08 | 0.12 | 0.18 | 0.26 |
| SOV (Skew of $\sigma$) | 0.69 | 1.05 | -0.51 | 0.05 | 0.62 | 1.28 | 2.04 |
| KOV (Kurt of $\sigma$) | 1.30 | 3.10 | -1.07 | -0.62 | 0.22 | 1.95 | 5.17 |

Panel F: Based on 5-Min Intraday Return Volatility, 277,678 observations (DEF.2)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| VOV (Vol of $\sigma$) / $\bar{\sigma}$ | 0.31 | 0.12 | 0.19 | 0.23 | 0.28 | 0.36 | 0.45 |
| SOV (Skew of $\sigma$) | 1.07 | 0.97 | 0.03 | 0.39 | 0.88 | 1.55 | 2.44 |
| KOV (Kurt of $\sigma$) | 2.30 | 4.00 | -0.75 | -0.25 | 0.78 | 3.20 | 7.72 |

Panel G: Correlation matrix of six volatility of volatility change measures

| | IMPLIED VOV (DEF.2) | EGARCH VOV (DEF.1) | EGARCH VOV (DEF.2) | INTRADAY VOV (DEF.1) | INTRADAY VOV (DEF.2) |
|---|---|---|---|---|---|
| IMPLIED - VOV (DEF.1) | 0.74 | 0.07 | 0.09 | 0.08 | 0.09 |
| IMPLIED - VOV (DEF.2) | | 0.10 | 0.14 | 0.09 | 0.15 |
| EGARCH - VOV (DEF.1) | | | 0.66 | 0.12 | 0.15 |
| EGARCH - VOV (DEF.2) | | | | 0.12 | 0.19 |
| INTRADAY - VOV (DEF.1) | | | | | 0.72 |

## 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 until month end for both call options and put options. The VOV measures are described in Table 2 and Table 3. 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. 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. INTADAY – VOV is calculated using daily intraday volatility calculated by five-minute log return provided by TAQ. In Panel A, VOV is defined as the standard deviation of percentage change of volatility ($\Delta\sigma/\sigma$) in each month (DEF. 1). In Panel B, VOV is defined as the standard deviation of volatility scaled by the average of volatility in each month. In Panel C, We use different dependent variables: delta-hedged gain till month-end / stock price, delta-hedged gain till month-end / option price, delta-hedged gain till maturity / ($\Delta$*S - C) and delta-hedged gain till week end / ($\Delta$*S - C). 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<br>Delta-hedged gain till month end<br>($\Delta$*S-C) | | | | Put Options<br>Delta-hedged gain till month end<br>(P - $\Delta$*S) | | | |
|---|---|---|---|---|---|---|---|---|
| **Panel A: Delta-hedged option return and volatility of volatility (DEF.1)** | | | | | | | | |
| 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: Delta-hedged option return and volatility of volatility (DEF.2)

| | Call Options | | | | Put Options | | | |
|---|---|---|---|---|---|---|---|---|
| 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*** |

Panel C: 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*** | -0.781** | 7.963** | -1.723*** | 0.119 |
| | (-4.42) | (1.85) | (-6.58) | (-2.98) | (-2.04) | (2.20) | (-2.99) | (0.76) |
| EGARCH - VOV | -0.275*** | -2.173*** | -1.101*** | -0.110*** | -0.529*** | -2.415*** | -0.765*** | -0.105*** |
| | (-6.52) | (-4.79) | (-8.02) | (-3.05) | (-8.38) | (-6.09) | (-7.89) | (-3.85) |
| 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 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. IVOL is 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). The realized volatility is the annualized 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 (2016). The volatility risk premium (VRP) 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) 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. To adjust for serial correlation, robust Newey-West (1987) t-statistics are reported in brackets.

| Fama-Macbeth | Call Options | | | |
|---|---|---|---|---|
| Regressions | Delta-hedged gain till maturity ($\Delta^*$S-C) | | | |
| Panel A: Control for volatility-related measures | | | | |
| 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 |

Panel B: Control for volatility risk premium

| | | | | |
|---|---|---|---|---|
| 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. 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 ($\Delta$*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. 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) | | | |
|---|---|---|---|---|
| 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 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. 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 the second through twelfth months 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. To adjust for serial correlation, robust Newey-West (1987) t-statistics are reported in brackets.

| Fama-Macbeth Regressions | Call Options<br>Delta-hedged gain till month end<br>(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 | | -0.645*** | -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: Option Portfolio Returns and Alphas (Sorted on VOV)

This table reports the average portfolio return sorted different measures of volatility of volatility (VOV). The return is defined as the return to covered calls till month end with daily rebalance. 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. At the end of each month, we rank all stocks with options traded into quintiles by different measures of VOV. For each stock, we sell one contract of call option against a long position of Δ shares of the underlying stock, where Δ is the Black-Scholes call option delta. The position is held for one month with rebalancing the delta position of the underlying stock at daily frequency. We use two weighting schemes in computing the average return to delta-hedged option return for a portfolio of stocks: equal weight (EW) and weight by the market value of option open interest at the beginning of the period (Option-OW). Panel B reports the return for each quintile portfolio and the spread return that is long in the fifth quintile and short in the first quintile. In Panel C, 3-factor Alpha is the alpha from the Fama-French 3-factor model. 3-factor Alpha is the alpha from the five-factor model including two additional factors: the momentum factor and the zero-beta straddle return of the S&P 500 Index option from Coval and Shumway (2001). 7-factor Alpha is the alpha from the 7-factor model including five factors and two additional factors: the change in the Chicago Board Options Exchange Market Volatility Index (ΔVIX) and the Kelly and Jiang (2014) tail risk factor. All returns in this table are expressed in percent. 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.

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 | Weights | 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 9: The 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 second column reports the average return spread of all stocks and all months. The third column reports the average return spread in the months without earning announcement. The fourth column reports the average return spread in the months with earning announcement. The fifth column reports the average return spread over the [-1,1] event window in the months with earning announcement. The sixth 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. To adjust for serial correlation, robust Newey-West (1987) t-statistics are reported in brackets.

| | 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 10: Higher Order Moments of Volatility (Change)

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. 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. To adjust for serial correlation, robust Newey-West (1987) t-statistics are reported in brackets.

| Fama-Macbeth Regressions | Call Options<br>Delta-hedged gain till maturity<br>($\Delta$*S-C) | | |
|---|---|---|---|
| | IMPLIED | EGARCH | INTRA-DAY |
| **Panel A: Definition 1 (DEF.1)** | | | |
| 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 |
| **Panel B: Definition 2 (DEF.2)** | | | |
| Volatility of (Volatility % change) | -3.383*** | -1.029*** | -2.124*** |
| | (-6.94) | (-5.96) | (-7.37) |
| Skewness of (Volatility % change) | -0.080*** | -0.016 | -0.100** |
| | (-3.98) | (-1.07) | (-2.67) |
| Kurtosis of (Volatility % change) | 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 |

## Table 11: Decomposition of Volatility Level

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 VOV measure is calculated with daily volatility estimated using EGARCH (1,1) model. For each stock, we first estimate daily total volatility $\sigma_t$ with a EGARCH (1,1) model using a rolling window of 252 days. Then we estimate daily idiosyncratic volatility $\sigma_{\varepsilon,t}$ using EGARCH (1,1) model with Fama-French 3 factors in the return equation of the model. Daily systematic volatility is then defined as $\sqrt{\sigma_t^2 - \sigma_{\varepsilon,t}^2}$. VOL of Idio Volatility is the standard deviation of percentage change in $\sigma_{\varepsilon,t}$ in the past month. VOL of Sys Volatility is the standard deviation of daily percentage change in systematic volatility in the past month. 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 ($\Delta$*S-C) | | | |
| | (1) | (2) | (3) | (4) |
| EGARCH - VOV | -0.797*** | | | |
| | (-7.83) | | | |
| VOL of Idio Volatility | | -0.869*** | | -0.822*** |
| | | (-5.62) | | (-5.24) |
| VOL of Sys Volatility | | | -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 12: Decomposition of Volatility Percentage Change

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. To decompose the daily percentage change in implied volatility, we use implied volatility of each stock as $\sigma_t$ and VIX index as $\sigma_{mt}$. To decompose the daily percentage change in EGARCH volatility, we first estimate daily volatility using a EGARCH(1,1) model with a rolling window of 252 days for each stock ($\sigma_t$ ) and for S&P 500 index ($\sigma_{mt}$ ). For each month and each stock, we then run the following regression with 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 percentage change of $\sigma_{mt}$. RMSE of $\hat{\epsilon_t}$ is defined as the idiosyncratic vol of change in vol. To adjust for serial correlation, robust Newey-West (1987) t-statistics are reported in brackets.

| 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 13: 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 as $\sigma_t$ and VIX index as $\sigma_{mt}$. 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 ($\sigma_t$) and for S&P 500 index ($\sigma_{mt}$). For each month and each stock, we run the following regression with monthly data (in the past 36 months): $vol\ of\ \frac{\Delta\sigma_t}{\sigma_t} = \alpha + \beta\ vol\ of\ \frac{\Delta\sigma_{mt}}{\sigma_{mt}} + \epsilon_t$. The decomposition of IMPLIED – VOV is similar to that of EGARCH – VOV. We then get $\hat{\beta}$ and the time series of residual $\hat{\epsilon_t}$. $\hat{\beta}$ is defined as the systematic exposure to market volatility of percentage change of $\sigma_{mt}$. RMSE of $\hat{\epsilon_t}$ is defined as the residual volatility of change in volatility. To adjust for serial correlation, robust Newey-West (1987) t-statistics are reported in brackets.

| 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 |

## Table 14: 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 change and VOV- is defined as the volatility of negative volatility percentage change 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-. Panel C shows bivariate regression results of VOV+ and VOV-. Panel D shows bivariate regression results of VOV and JOV. Column 2-4 and Column 6-8 show regression results for measures based on IMPLIED, EGARCH and INTRADAY volatility. To adjust for serial correlation, robust Newey-West (1987) t-statistics are reported in brackets.

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 |