Why Does Volatility Uncertainty Predict Equity Option Returns?†

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Abstract

Delta-hedged option returns consistently decrease in volatility of volatility changes (volatility uncertainty), for both implied and realized volatilities. We provide a thorough investigation of the underlying mechanisms including model-risk and gambling-preference channels. Uncertainty of both volatilities amplifies the model risk, leading to a higher option premium charged by dealers. Volatility of volatility-increases, rather than that of volatility-decreases, contributes to the effect of implied volatility uncertainty, supporting the gambling-preference channel. We further strengthen this channel by examining the effects of option end-users net demand and lottery-like features, and by decomposing implied volatility changes into systematic and idiosyncratic components.

Keywords: Delta-hedged option returns, volatility uncertainty, volatility-of-volatility, model risk, gambling preference

JEL Classification: G10, G12, C58, D80

1. Introduction

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

In this paper, we study whether the uncertainty of volatility changes predicts future cross-sectional equity option returns and focus on the channels that drive this predictability. Previous studies point out that option arbitrageurs in imperfect markets face "model risk", especially when they write options (e.g., Figlewski (1989, 2017) and Green and Figlewski (1999)). Green and Figlewski (1999) show that an important source of model risk is that not all of the input parameters, especially the volatility parameter, are observable. Even if one has a correctly specified model, using it requires knowledge of the volatility of the underlying asset over the lifetime of the contract. Consequently, option arbitrageurs face higher model risk when the volatility parameter is more uncertain. 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 or market makers (dealers). For example, to mitigate the risk associated with volatility uncertainty, risk-averse option writers charge a higher premium to compensate for model risk, leading to lower option returns for buyers. Similarly, dealers

[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 e.g., Barndorff- Nielsen and Shephard (2002); Andersen, Bollerslev, Diebold, and Labys (2003)).

[2] Representative work of empirical studies on the pricing of volatility in the stock market include Ang, Hodrick, Xing, and Zhang (2006) and Barndorff-Nielsen and Veraart (2013). More recently, Campbell, Giglio, Polk, and Turley (2018) introduce an intertemporal CAPM with stochastic volatility.

may find that model risk increases their hedging cost during their market-making process. These costs will be incorporated into option prices, taken by option end-users.

Besides model risk faced by the dealers or option writers, volatility uncertainty may have an impact on the net speculative demand of option end-users, through a gambling-preference channel in the options market.[3] Since the option value is positively correlated with volatility, the high uncertainty of volatility-increases could attract more net speculative demand from option end-users. According to the demand-based option pricing theory (Gârleanu, Pedersen, and Poteshman (2009)), a higher net speculative demand from end-users pushes up option prices and leads to lower subsequent option returns. In contrast, the uncertainty of volatility decreases might depress the net speculative demand from option end-users. Therefore, if some option end-users indeed gamble on future volatility changes, we would expect the negative effect of volatility uncertainty on option returns, if any, to be driven by the uncertainty of volatility-increases.

In a stylized stochastic volatility model, we measure volatility uncertainty as the standard deviation of the percentage change of the daily volatility level over a month. Hereafter, we refer to this measure as volatility-of-volatility (VOV). Empirically, we use three estimates of volatility to calculate VOV: (1) implied volatility from 30 days to maturity options, (2) realized volatility estimated from an EGARCH (1,1) model using rolling 252 days, and (3) intraday realized volatility from five-minute returns. We then compute the standard deviation of the percentage change of the daily volatility level over the previous month to define the three measures of VOV.[4]

We measure the delta-hedged option return of individual stocks following Bakshi and Kapadia (2003) and Cao and Han (2013). Delta-hedging allows us to remove the

[3] Previous studies have emphasized the potential role of gambling in investment decisions (Markowitz (1952), Barberis and Huang (2008)), and many have documented supportive evidence from the stock market, for example, Kumar (2009), Bali, Cakici, and Whitelaw (2011), Bali, Brown, Murray, and Tang (2017), etc.

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

confounding effects of VOV on underlying stock returns, which have been documented in Baltussen, Van Bekkum, and Van Der Grient (2018). Fama-MacBeth regressions report a negative and significant relation between each VOV estimate and monthly delta-hedged option returns, for both call and put. Multivariate regressions reveal that the coefficients of the three VOV measures are robust after controlling for many known option return predictors documented in the literature.

To investigate the economic magnitude of the predictability, we form quintile portfolios of delta-neutral call writing strategies sorted on VOV. To remove the exposure to stock price movements, we perform daily rebalancing of the stock position as delta changes and compound the daily return of such delta-hedged call option position to obtain the monthly return. At the end of each month, we sort all stocks in our sample by their VOV measures and form quintile portfolios of writing delta-neutral calls. We find that average returns increase monotonically from quintile 1 to quintile 5. The return spreads between the top and bottom quintiles are statistically significant for the three VOV measures ranging from 0.52% to 1.04% per month. The results are robust to different weighting schemes. 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 explore the underlying mechanism through which these VOV measures predict equity option returns, we investigate the role of option demand pressure on the predictability of VOV. We find that option demand pressure is positively related to implied VOV measure, but negatively related to the two realized VOV measures. Such preliminary evidence indicates that the negative effect of implied VOV on option returns could be partially attributed to a higher demand pressure. In contrast, the negative effect of realized VOV is less likely to be related to demand pressure. We further control for demand pressure and find that it does not subsume the predictability of VOV on option returns, suggesting that the model-risk hypothesis holds for both implied and realized VOV measures.

To formally investigate the gambling-preference channel, we decompose VOV into two semi-variance measures: VOV+ and VOV-. VOV+ is the standard deviation of the positive percentage change of volatility and VOV- is the standard deviation of the negative percentage change of volatility.[5] For implied VOV measure, univariate regressions show that VOV+ has a large negative impact on future option returns, while the impact of VOV- is not significant. The results of multivariate regressions with both VOV+ and VOV- confirm the negative effect of VOV+, while the effect of VOV- becomes significantly positive. This observation is consistent with the hypotheses that option buyers (writers) with gambling-preference prefer the uncertainty of volatility-increases (decreases), which leads to a higher (lower) option price and a lower (higher) future option return. However, the results of the realized VOV measures are again different from those of implied VOV. Both realized VOV+ and VOV- are significantly and negatively related to future option returns. These results suggest that option market makers or proprietary traders might be using realized volatility for market making and arbitrage. [6] Realized volatility changes, both upward and downward, increase their hedging costs and lead to an increment in the option price.

To better understand the different findings of implied VOV and realized VOV measures, we further examine the role of option end-users net demand which is not from option maker makers or proprietary traders (including brokers/dealers). Specifically, we utilize signed option volume data from the International Securities Exchange (ISE) open/close trade profile to compute option order imbalance from public customers, who

[5] For this decomposition, we follow the spirit of Patton and Sheppard (2015) and Bollerslev, Li, and Zhao (2020), in which the authors decompose the volatility into two semi-variance measures associated with positive and negative stock returns, respectively.

[6] Option traders with gambling preferences might not utilize realized VOV measures which are not readily available and require higher computational capacity to process high frequency data or apply advanced econometric tools. However, option market makers use many different realized volatility models with daily and intraday return data to help forecast volatility and manage risk exposure.

are more likely to have gambling preferences. We then interact VOV+ and VOV- with the option order imbalance measure. Consistent with the gambling-preference channel, we find that option order imbalance from public customers only significantly enhances the negative effect of implied VOV+, but not the one of the realized VOV+ measures. Such evidence again suggests that gambling preferences partially explain the option return predictability of the implied VOV measure.

Along the line of gambling preference, we further explore the effect of lottery-like features (extreme changes in implied volatility) on our findings of implied VOV+ and VOV-. We find that extreme increases and decreases in implied volatility could explain almost 50% of the (opposite) effects of implied VOV+ and implied VOV- on option returns, supporting the gambling-preference channel beneath the predictability by implied VOV measure.

In a similar vein as in Ang, Hodrick, Xing, and Zhang (2006) which define idiosyncratic volatility of daily stock returns, we decompose daily volatility change into two components by regressing the implied volatility change of the stock on the contemporaneous change in VIX. We obtain a systematic exposure to market volatility changes, namely systematic-VOV, and a daily idiosyncratic component of volatility change. Then for each month and each stock, we calculate the standard deviation of this idiosyncratic component, namely the idiosyncratic-VOV. Consistent with the gambling-preference channel, we find that the idiosyncratic-VOV is the driving component for the negative relation between implied VOV and option returns. Such evidence echoes the well-known idiosyncratic volatility (IVOL) puzzle in the stock market (see e.g., Ang, Hodrick, Xing, and Zhang (2006) and Bali, Cakici, and Whitelaw (2011)).

Our paper contributes to several strands of literature. First, we contribute to the growing literature of option pricing. Volatility-related information has been documented to predict option returns, for example, Goyal and Sarreto (2009), Cao and Han (2013), and Vasquez (2017). Other studies have documented the predictability by stock skewness

(Bali and Murray (2013), Boyer and Vorkink (2014)), option illiquidity (Christoffersen, Goyenko, Jacobs, and Karoui (2018)), option market order-flow imbalance (Muravyev (2016)), many firm characteristics (Zhan, Han, Cao, and Tong (2022)), firm leverage (Vasquez and Xiao (2022)), short-sale constraints (Ramachandran and Tayal (2021)), etc. Our paper is among the first to study how the uncertainty in time-varying volatility affects cross-sectional delta-hedged option returns. Moreover, we provide a thorough investigation of the underlying mechanisms including model-risk and gambling-preference channels.

Second, our paper explores the impact of volatility uncertainty on the equity options market. Previous studies have examined the impact of volatility-of-volatility in other financial markets, such as the stock market (Baltussen, Van Bekkum, and Van Der Grient (2018)) and the hedge-fund market (Agarwal, Arisoy, and Naik (2017)). Several researchers (for example, Chen, Chordia, Chung, and Lin (2022), and Hollstein the and Prokopczuk (2018)) study the impact of the stock market VOV as a systematic risk factor. Huang, Schlag, Shaliastovich, and Thimme (2019) document the effect of the volatility-of-volatility-index (VVIX) on index options and VIX options. We contribute to this literature by focusing on the effect of stock-level VOV on the cross-sectional delta-hedged return of equity options.[7]

Last, several studies document the impacts of gambling preferences on price movements in the stock market. Our paper is the first one that investigates gambling preferences on volatility changes in the equity options market. Consistent with the cross-sectional stock return literature, such as Kumar (2009) and Bali, Cakici, and Whitelaw (2011), we find the option return predictability by implied VOV is driven by implied VOV+, while implied VOV- has an opposite effect on option returns. We find corroborating evidence for gambling preference by examining the net demand by option

[7] 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, Van Bekkum, and Van Der Grient (2018).

end-users. Moreover, lottery-like features proxied by extreme volatility changes could explain almost half of the effects of implied VOV+ and VOV-. Finally, when we decompose implied VOV into systematic and idiosyncratic components, we find the latter drives the results, consistent with the gambling preference. Our findings also echo and complement the studies about behavioral explanations for the idiosyncratic volatility puzzle in the stock market. We apply these behavioral explanations to the equity options market, where volatility is a traded asset.

A parallel independent work by Ruan (2020) has a similar finding that implied VOV negatively predicts the cross-section of option returns. However, there are several significant differences between our study and Ruan (2020). We comprehensively study three measures of volatility (implied, EGARCH, and intraday volatilities) instead of one, so that we explore both implied and realized volatility measures. More importantly, our focus is the mechanisms, and we uncover that two non-mutually exclusive channels, i.e., model risk and gambling preference in the options market, contribute to our documented findings. Specifically, model risk applies to both implied VOV and realized VOV measures, yet gambling preference only applies to the implied VOV measure. To support the gambling preference of implied VOV, we find the volatility of volatility-increases, rather than that of volatility-decreases, contributes to the effect of the implied VOV measure. We further strengthen this channel by examining the impact of option end-users net demand and lottery-like features and decomposing implied volatility changes into systematic and idiosyncratic components.

The rest of the paper is organized as follows. Section 2 describes our data and measures. Section 3 explores whether and how volatility uncertainty predicts delta-hedged option returns. Section 4 further investigates the gambling-preference channel, and Section 5 concludes.

2. Data and Variables

2.1. Data and sample coverage

Option data on individual stocks are from the OptionMetrics Ivy DB database. The database contains information on the entire U.S. equity options market, including daily closing bid and ask quotes, open interest, and volume from January 1996 to April 2016. Options' delta and other Greeks are calculated by OptionMetrics using the binomial tree from Cox, Ross, and Rubinstein (1979). We extract implied volatility information from OptionMetrics Volatility Surface, which contains implied volatilities for options with fixed time to expiration and deltas constructed using interpolation. We obtain other data as follows: stock returns, prices, and trading volume from the Center for Research on Security Prices (CRSP), annual accounting data from Compustat, quarterly institutional holding data from Thomson Reuters (13F), analyst coverage and forecast data from I/B/E/S, and high frequency data of stock prices from the TAQ database.

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 (ATM) and expire on the third Friday/Saturday of the month after the next. For example, on June 30, 2011, we select options expiring on August 20, 2011.[8] For a given month, all options we study have the same expiration day and our cross-sectional analysis is not influenced by the difference in maturities. We focus on these options because short-term ATM options are traded more frequently and with lower effective transaction costs compared to long-term options or expiring options. We apply several filters to the option data. First, to avoid illiquid options, we exclude options if the monthly trading volume is zero, the bid quote is zero, the bid quote is smaller than the ask quote, or the average of the bid and ask price is lower than \$1/8. Second, to remove the effect of early exercise premium in American options, we discard options whose underlying stock pays a dividend during the remaining life of the

[8] The growth of weekly options after 2013 generates multiple option expiration dates in each month. However, the third Friday/Saturday is still the most common maturity date for equity options.

option. Therefore, options in our sample are very close to European style options. Third, we exclude all options that violate no-arbitrage restrictions. Fourth, we only keep options with moneyness between 0.8 and 1.2.[9]

Table 1 reports the summary statistics of the call and put options in our sample. Our final sample contains 327,016 option-month observations for calls and 305,710 option-month observations for puts. The average moneyness of the call options and the put options are both close to 1 with a standard deviation of 5%. The time to maturity ranges from 47 to 50 days. The 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, raw option returns are highly sensitive to stock returns. Thus, as per the literature, we study the gain of delta-hedged options, so that the portfolio gain is not sensitive to the movement of the underlying stock. In the Black-Scholes model, the expected gain of a delta-hedged option portfolio is zero because the option position can be completely hedged by the position on the underlying stock. Empirical studies find that the average gain of the delta-hedged option portfolios is negative for both indexes and individual stocks (Bakshi and Kapadia (2003), Carr and Wu (2009), and Cao and Han (2013)).

We measure the delta-hedged call option return following Bakshi and Kapadia (2003) and Cao and Han (2013). We first define the daily rebalanced delta-hedged option gain, which is the change in the value of a self-financing portfolio that consists of a long call position, hedged by a short position in the underlying stock such that the portfolio is not sensitive to the stock price movement, with the net investment earning the risk-free

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

rate. 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

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

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

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

where Δ_{C,t_n} is the delta of the call option on date t_n, r_{t_n} is the annualized risk-free rate on date t_n, and α_n is the number of calendar days between t_n and t_{n+1}. The definition of the delta-hedged put option gain replaces the call price and call delta by the put price and put delta in equation (2). To make the option return comparable across stocks, we follow Cao and Han (2013) and scale the delta-hedged gain by the initial investment of the option portfolio, which is $(\Delta_{c,t} S_t - C_t)$ for call options and $(P_t - \Delta_{p,t} S_t)$ for put options, respectively.[10]

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

[10] We obtain similar results when we scale by the initial price of the underlying stocks or by that of options.

Panel A.1 and A.2 of Table 1 present the summary statistics of delta-hedged option returns for call and put options, respectively. Consistent with the findings of Cao and Han (2013), the average delta-hedged returns of individual equity options are negative for both calls and puts. On average, the delta-hedged gain until month-end for call (put) is −0.82% (−0.48%) over next month. There is substantial cross-sectional variation in these gains. For example, the lower and the upper quartile of delta-hedged call option gains are −2.66% and 0.75%, respectively.

[Insert Table 1 about here]

2.3. Volatility-of-volatility (VOV) measures

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

The first measure of daily volatility is extracted from the Volatility Surface provided by OptionMetrics. The advantage of using the Volatility Surface is that daily implied volatilities have constant maturities and deltas. Specifically, we selected ATM implied volatilities with 30 days of maturity and delta equal to 0.5 (-0.5) for call (put) options. The daily implied volatilities are calculated as the average of the ATM call and ATM put implied volatilities. Then we use the daily implied volatilities within a given month to calculate the monthly VOV.[11]

The second measure of daily volatility is estimated using the following EGARCH (1,1) model with daily stock returns[12]:

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

[12] 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. Previous studies, such as Fu (2009) and Cao and Han (2016), use EGARCH models to estimate time-varying volatility for a large cross-sectional sample of stocks.

$$r_t = \sigma_t z_t; \quad ln\sigma_t^2 = \omega + \alpha\ r_{t-1}^2 + \beta\ ln\sigma_{t-1}^2 + \gamma\left[|z_{t-1}| - (\tfrac{2}{\pi})^{\frac{1}{2}}\right], \tag{3}$$

where r_t is the stock return, σ_t is the conditional volatility, and z_t is the innovation term. For each stock in a given month, we apply the EGARCH (1, 1) model to a rolling window of the past 12-months' daily stock returns (including the current month).[13] This generates a series of time-varying realized volatility levels for each day within the estimation window. The maximum number of iterations is 500 for the maximum likelihood estimation and over 96% of the EGARCH regressions in our sample successfully converge.

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

For the three measures of daily volatility, we calculate the daily percentage change in volatility (volatility-return), as $\frac{\Delta\sigma}{\sigma} = \frac{\sigma_t - \sigma_{t-1}}{\sigma_{t-1}}$, where σ_t is the volatility on day t. We define the monthly VOV measure as the standard deviation of the daily volatility-return within each month. This definition of VOV is different from the measure in Baltussen, Van Bekkum, and Van Der Grient (2018), where it is the standard deviation of implied volatility scaled by the average implied volatility level within each month. The correlation between the two VOV definitions is around 0.7. The main reason to define our VOV measure based on volatility-return is to be in line with the *VVIX index* from CBOE. *VVIX* according to the CBOE website is defined as the implied volatility of VIX futures returns. If we consider volatility as an asset, similar to a stock, then the volatility of this asset is defined based on its return.

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

Figure 1 shows the distributions of the three daily volatility levels (Panels A, B, and C) and of their volatility-returns (Panels D, E, and F). The distribution of all three daily volatility measures resembles the log normal distribution. In contrast, the distribution of the daily volatility-returns exhibits a symmetric bell shape. This result provides support for using the standard deviation of volatility-returns to estimate the volatility-of-volatility used in our analyses.

[Insert Figure 1 about here]

Table 1 also reports summary statistics for the three daily volatility and volatility-of-volatility (VOV) measures in Panels B.1, B.2, and B.3, respectively. All volatility measures are annualized. The means of the three daily volatility measures are very similar: 0.48 for implied volatility, 0.47 for EGARCH volatility, and 0.45 for intra-day return volatility. The estimates of VOV, however, differ across the three measures. *INTRADAY-VOV* has the highest mean at 0.39 and *EGARCH-VOV* has the lowest mean at 0.19; the volatility from high-frequency returns is more volatile than the volatility from low frequency (daily) returns.

Panel B.4 of Table 1 reports the cross-sectional correlations among the three VOV measures. The correlations among the VOV measures are between 0.07 and 0.12. The low correlations among the VOV measures suggest that the three measures contain distinct information. Option implied volatility is a forward-looking estimate of the volatility in the next 30 days. Since option prices are usually quoted in implied volatility, *IMPLIED-VOV* may capture the uncertainty of historical option price changes. Option trader's expectations might be affected more by *IMPLIED-VOV* than by the other two realized VOV measures. The EGARCH measure uses daily stock returns to estimate daily conditional volatility, and the intraday VOV measure uses high-frequency data that contains information not present in the other two measures. Option market participants may utilize different information sets, e.g., from historical stock return data, historical option price data, or high frequency data, for different motives, such as risk management, market making, trading, or speculating. Therefore, it remains an unanswered empirical question whether and how these VOV measures predict future option returns.

3. Empirical Results

3.1. A robust relation between the three VOV measures and future option returns

We first examine the empirical relation between three VOV measures and future delta-hedged option returns. Table 2 Panel A reports the results of Fama-MacBeth regressions. The coefficients of the three VOV measures are significantly negative for both call and put options, with an average t-statistics above 6. When we include all three VOV measures in a multivariate Fama-MacBeth regression, all coefficients remain almost unchanged. We also observe an increased adjusted R-squared, which is almost the sum of that of the three univariate regressions. The evidence suggests that the three VOV measures capture independent information and together can explain a larger portion of cross-sectional option returns. The results remain unchanged when using the alternative VOV definition from Baltussen, Van Bekkum, and Van Der Grient (2018) as reported in Table A1 of the Internet Appendix.

[Insert Table 2 about here]

We further check the robustness of our results to alternative definitions of option returns. Table 2 Panel B reports the multivariate regression results of three VOV measures on four alternative definitions of option returns: i) delta-hedged gain until month-end scaled by stock price, ii) delta-hedged gain until month-end scaled by stock price, iii) delta-hedged gain until maturity scaled by initial investment, and iv) delta-hedged gain until week-end scaled by initial investment. As shown in Panel B, our results are robust to the alternative variables used to scale the delta-hedged gain as well as to the holding periods of the return.

To understand whether this empirical relation could point to a potentially profitable trading strategy, we use sort equity options into portfolios using three VOV measures. Following the portfolio analysis in Cao and Han (2013), we work with delta-neutral call writing on individual stocks, which contains a short position in an ATM call option and a long position of delta-shares of the underlying stocks.[14] The position is held for a month with daily rebalancing of the delta hedge. For each stock, we compound the daily return of the rebalanced delta-hedged call option position to obtain the monthly return.

Every month we sort all optionable stocks into five quintiles.[15] We rank stocks based on four VOV measures: *IMPLIED-VOV*, *EGARCH-VOV*, *INTRADAY-VOV*, and a *Combined-VOV*. The combined VOV measure is the average of the ranking percentile of the three individual VOV measures.[16] For each of the three VOV variables, we assign a rank to each stock option that reflects the sorting on that VOV variable. The composite rank is then the arithmetic average of the ranking percentile of the three VOV variables.

Table 2 Panel C reports the average return for each quintile portfolio and the return (risk-adjusted) spread between the top and bottom quintile portfolios. We report Newey-West (1987) t-statistics to adjust for serial correlations. We find that the portfolio returns increase monotonically from quintile 1 to 5 for the four VOV measures in both weighting schemes.[17] For the equal-weighting (EW) scheme, the (5-1) spread portfolios ranked by *IMPLIED-VOV*, *EGARCH-VOV*, and *INTRADAY-VOV* generate monthly

[14] Note that we consider the return of buying delta-hedged options in the regression analysis, while we consider the return of selling the delta-hedged options in the portfolio analysis.

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

[16] This methodology is used by Stambaugh, Yu, and Yuan (2015), in which they combine multiple stock market anomalies into a composite score.

[17] The average return to delta-neutral call writing is positive. The result is consistent with the negative return for delta-hedged options, a portfolio that is long the option and short the underlying stock, which is opposite to a delta-neutral call writing.

returns of 0.88%, 0.52%, and 0.47% with corresponding t-statistics of 13.77, 10.46, and 5.28, respectively. For the *Combined-VOV* we find that the magnitudes of the return spread and the t-statistics are higher than those of the individual VOV variables. The results are robust to different weighting methods and to different asset pricing modelds.[18]

We further investigate whether the effects of VOV measures can be explained by different sets of control variables such as volatility level, volatility-related mispricing, variance and jump risk, liquidity, or information uncertainty and asymmetry, etc. Each month, we conduct cross-sectional regressions of delta-hedged option returns on VOV measures and one or more control variables. To save space, we report the results based on call options and the results for put options are similar to those for call options. In summary, our findings of the negative predictability by VOV are novel and cannot be explained by findings in previous literature. Detailed discussions for these results are reported in the Internet Appendix.

3.2. Two channels behind the predictability of VOV measures

After establishing a robust relation between three VOV measures and option returns, we aim to understand the underlying mechanisms behind such predictabilitiy. Two non-mutually exclusive mechanisms could drive the relation, i.e., a model-risk channel and a gambling-preference channel. First, underlying stocks with higher VOV may impose higher model risk. Specifically, pricing and hedging errors due to inaccurate volatility estimates create sizable risk exposure for option writers or market makers (dealers). Therefore, there is a higher premium to compensate for model risk, leading to lower option returns for buyers. Second, it is also possible that option end-users have speculative demand and they gamble with options written on underlyings with higher volatility

[18] Specifically, we control for the Fama and French (1993) three factors, the momentum factor (Carhart (1997)), and the Kelly and Jiang (2014) tail risk factor. We also control for two volatility factors: the zero-beta straddle return of the S&P 500 Index option (Coval and Shumway (2001)), and the change in VIX, the Chicago Board Options Exchange Market Volatility Index (Ang, Hodrick, Xing, and Zhang (2006)).

uncertainty. Intuitively, option value is positively correlated with volatility, therefore, a higher magnitude of volatity increase would attract more net speculative demand from option end-users, pushing up the option prices and lowering option returns according to to the demand-based option pricing theory (Bollen and Whaley (2004); Gârleanu, Pedersen, and Poteshman (2009)). In contrast, a higher magnitude of volatility decreases might depress the net speculative demand from option end-users.

3.2.1 Volatility-of-volatility and option demand pressure

While the two channels could coexist, one important distinction is the impact of VOV on option end-user demand. If some option traders indeed gamble on the volatility changes, we would expect the VOV measures to have a positive impact on option demand pressure. After controlling for demand pressure, if the VOV measures are still significant, the remaining effects could be attributed to model risk.

We measure option demand pressure as the option open interest scaled by the stock volume. 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. In Panel A of Table 3, we find that demand pressure is positively related to *IMPLIED-VOV*, but negatively related to *EGARCH-VOV* and *INTRADAY-VOV*. The stark constrast between implied volatility- and realized volatility-uncertainty measures indicate that option traders with gambling prefereces tend to focus on *IMPLIED-VOV* to make their trading decisions. The negative effect of realized VOV measures on option returns is unlikely through the demand channel, given the documented negative relation between realized volatility uncertainty and demand pressure. Therefore, the realized VOV measures are more likely to be used by option market makers or proprietary traders for market making and arbitrage.

Since *IMPLIED-VOV* is positively related to demand pressure, we next check whether the predictability of *IMPLIED-VOV* still exists after controlling for demand pressure to isolate the model risk channel. Panel B of Table 3 reports regression results of VOV on delta-hedged call option returns after controlling for demand pressure. We find that the three VOV variables remain significantly negative and experience a 20% reduction in economic magnitudes. Even though options with high *IMPLIED-VOV* are subject to higher demand pressure, the demand pressure per se cannot fully subsume the predictability of *IMPLIED-VOV*. Such preliminary evidence indicates that the negative effect of *IMPLIED-VOV* on option returns could be partially attributed to both model-risk and gambling-preference channels. In contrast, the effect of realized VOV measures is more likely to be related to model-risk channel.

[Insert Table 3 about here]

3.2.2 Volatility of volatility-increases vs. volatility of volatility-decreases

Another implication of gambling preferences in the options market is that option buyers prefer positive future changes in volatility rather than negative changes in volatility while option writers prefer the opposite. Hence, for option buyers (writers) with gambling preferences, volatility of volatility-increases (decreases) is more appealing. To test such hypothesis, we decompose VOV into two semi-variance measures: VOV+ and VOV-. VOV+ is the standard deviation of the positive percentage changes of volatility and VOV- is the standard deviation of the negative percentage changes of volatility.[19] Our decomposition is similar to the method used in Patton and Sheppard (2015) and Bollerslev, Li, and Zhao (2020). These two papers decompose stock return volatility into two semi-variance measures from the shareholders' perspective. Specifically, they define "good" and "bad" volatility associated with positive and negative stock price increments, respectively.

[19] We use the daily volatility information of previous month to calculate VOV+ and VOV-, the same as we calculate VOV. In some cases, the measure construction suffers from insufficient number of observations. Our results hold if we construct these measures using volatility data from past two months.

We hypothesize that option buyers with gambling preferences are willing to pay a higher premium for options with a higher chance of volatility-increases (VOV+) while option writers with gambling preferences tend to charge a lower premium for options with higher chance of volatility decreases (VOV-). Therefore, options with higher VOV+ (VOV-) have lower (higher) future returns. In contrast, the model-risk channel predicts that the impacts of VOV+ and VOV- on option returns should be both negative. The higher chance of volatility changes, regardless of the directions, amplifies the difficulty in hedging for option market makers, leading to an increment in the option price and a lower future option return.

Table 4 reports the Fama-MacBeth regression results of VOV+ and VOV- measures for each VOV variable. Panels A and B show the univariate regression results of VOV+ and VOV-, respectively. Panel C presents multivariate regression results with both VOV+ and VOV- included. For implied VOV measures, univariate regressions results show that VOV+ has a large negative impact on future delta-hedged option returns, with t-statistics of -6.78, while the impact of VOV- is not statistically significant. The results of multivariate regressions with both VOV+ and VOV- confirm the negative effect of VOV+, while the effect of VOV- turns significantly positive. This observation is consistent with our hypotheses that option buyers (writers) with gambling-preferences prefer the uncertainty of volatility-increases (decreases), which leads to a higher (lower) option price and a lower (higher) future option return.

[Insert Table 4 about here]

Both the VOV+ and VOV- measures based on EGARCH and INTRADAY volatilities significantly and negatively predict delta-hedged option returns, in either univariate or multivariate regressions. Such evidence supports the model-risk channel for the predictability of these two realized VOV measures. The contrast between the implied

VOV and the realized VOV measures indicates that gambling preferences only applies to the implied VOV, but not to the realized VOV measures. Why is that? Option traders with gambling preferences might not utilize realized VOV measures since they might believe it is not directly related with the price of the options. Also realized VOV measures are not readily available and require higher computational capacity to process high frequency data or apply advanced econometric tools. However, option market makers use implied volatility information as well as many different realized volatility models with daily and intraday return data to help forecast volatility and manage risk exposure.

It is worth noticing that implied VOV- has an insignificant effect on option returns in univariate regression. One possible reason could be that the positive impact predicted by the gambling-preference channel is offset by the negative impact predicted by the model-risk channel. It is also possible that retail investors with gambling preferences are more likely to buy options rather than write options. Writing options is subject to much higher capital requirements, for example, to cover the costs of maintaining margins and dynamic hedges. Therefore, the gambling preference may have a stronger impact on implied VOV+ than on implied VOV-, and the overall effect of implied VOV on delta-hedged option returns is negative. Such pattern also indicates high net speculative (buying) demand associated with high VOV options.

Another implication of gambling preference is that the effect of implied VOV+ on delta-hedged option return would be stronger when there is a high net demand from option end-users (public customers), who are more likely to have gambling preferences. We utilize the signed option volume data from International Securities Exchange (ISE) open/close trade profile to compute option order imbalance (*OOI*) from public customers, who are not option maker makers or proprietary traders. Following Ramachandran and Tayal (2021) and Chen, Joslin, and Ni (2019), we calculate *OOI* as the monthly cumulative difference of signed option volumes across contracts.[20] If the above arguments are correct, we would expect to find a stronger impact of implied VOV+ on delta-hedged option returns when *OOI* is higher, i.e., more net buying demand from public customers.

In Panel D of Table 4, we document a significant and negative coefficient on the interaction between implied VOV+ and *OOI*. This result is consistent with our expectation that gambling preferences enhance the impact of VOV+ on delta-hedged option returns. The coefficients are insignificant for the interaction terms when we construct VOV+ based on EGARCH and INTRADAY volatilities. These results further validate our findings from previous sections that option end-users with gambling preferences prefer to use implied volatility information.

4. A Closer Look at the Gambling-Preference Channel

Our earlier evidence shows that there is a gambling-preference channel behind the predictability by implied volatility uncertainty. In this section, we focus on implied volatility uncertainty and attempt to provide more corroborating evidence for the gambling preference channel.

4.1. Controlling for extreme changes in implied volatility as the lottery-like features

Barberis and Huang (2008) posit that investors might overweight low probability events and exhibit a strong gambling preference for lottery-like securities. Bali, Cakici, and Whitelaw (2011) find supporting empirical evidence for the theory in Barberis and Huang (2008) by examining the effect of extreme stock returns on the cross-sectional pricing of stocks. Following the spirit of Bali, Cakici, and Whitelaw (2011), we employ extreme changes in implied volatility as the lottery-like features for the investors who may gamble

[20] *OOI* is calculated as the cumulative difference between the sum of buying volume from initiating long positions (open buy) and the sum of selling volume from initiating short positions (open sell).

on implied volatility changes.[21]

We expect that option buyers with gambling preferences prefer the extreme increase of implied volatility, which leads to a higher option price and a lower future option return. We construct *IMPLIED-MAX(5)* as the average of the highest five daily percentage changes in implied volatility over the previous month. *MAX(5)* captures the extreme implied volatility increase and may explain the negative effect of implied VOV+ on option returns. On the other hand, option writers with gambling-preferences would prefer the extreme decrease of implied volatility which leads to a lower option price and a higher future option return. We also define *IMPLIED-MIN(5)* as the negative of the average of the lowest five daily percentage changes in implied volatility over the previous month to capture the extreme implied volatility decreases. We expect that MIN(5) may explain the positive effect of implied VOV- on option returns.

If gambling preference is indeed a channel through which implied VOV+ and implied VOV- predict delta-hedged option returns as shown in Table 4, we would expect these predictabilities to be weakened when lottery-like features are included in the regressions. Table 5 reports the multivariate Fama-MacBeth regressions results. Consistent with the gambling-preference channel, we find that *IMPLIED-MAX(5)* and *IMPLIED-MIN(5)* carry a significantly negative and positive coefficient, respectively. The opposite effects of *MAX(5)* and *MIN(5)* support the cumulative prospect theory (Barberis and Huang (2008)), and are consistent with the stock market results as documented in Bali, Cakici, and Whitelaw (2011).[22] The impact of implied VOV+ and implied VOV- still holds after controlling for the extreme changes in implied volatility, but the magnitudes reduce by about a half. These findings further lend support to our argument that option traders indeed have gambling preferences and such preferences contribute to

[21] As documented earlier, option traders with gambling preferences are likely to use implied volatility information, so we focus on implied volatility changes in this subsection.

[22] Bali, Cakici, and Whitelaw (2011) show a negative effect of MAX and a positive effect of MIN on future stock returns in their Table 10.

the predictability of implied VOV in the options market.

[Insert Table 5 about here]

4.2. Decomposing implied volatility changes: Systematic-VOV vs. Idiosyncratic-VOV

Kumar (2009) also tests the gambling preference in the stock market using idiosyncratic volatility of stock returns as a lottery-like feature. We extend the investigation to the option market. In a similar vein as in Ang, Hodrick, Xing, and Zhang (2006) that defines idiosyncratic volatility of daily stock returns, we decompose the daily percentage change of volatility into the systematic and idiosyncratic components by regressing the implied volatility change of individual stocks on the contemporaneous change in VIX. Therefore, we obtain a systematic exposure to market volatility changes, namely *Systematic-VOV*, and a daily idiosyncratic component of volatility change. Then for each month and each stock, we calculate the standard deviation of this idiosyncratic component, namely the *Idiosyncratic-VOV*.

Empirically, we regress the daily percentage change of implied volatility (σ_t), on the daily percentage change of VIX index (σ_{mt}) by running the following regression for each stock and each month:

$$\frac{\Delta\sigma_t}{\sigma_t} = \alpha + \beta\frac{\Delta\sigma_{mt}}{\sigma_{mt}} + \epsilon_t, \tag{4}$$

Where ϵ_t is the idiosyncratic component of the daily percentage change of implied volatility. *Systematic-VOV* is measured by β, the systematic exposure to the percentage change of σ_{mt} (*Beta to (%Δ in MKT Vol)*). *Idiosyncratic-VOV* is measured as the standard deviation of ϵ_t, *Vol of (idio %Δ in Vol)*.

[Insert Table 6 about here]

Table 6 reports the Fama-Macbeth regressions of delta-hedged call option returns on *IMPLIED-VOV*, *Systematic-VOV*, and *Idiosyncratic-VOV*. The coefficient of *Idiosyncratic-VOV* is negative and significant while the coefficient of *Systematic-VOV* is significantly positive. When we run a multivariate Fama-Macbeth regression with both *Systematic-VOV and Idiosyncratic-VOV*, we confirm the findings from the univariate regressions. The strong negative effect of *Idiosyncratic-VOV* on option returns is consistent with the findings in the stock market. Moreover, the univariate regression with *Idiosyncratic-VOV* as the independent variable has the highest adjusted R-square, suggesting that *Idiosyncratic-VOV* is the more dominant component of *IMPLED-VOV*. Such evidence also echoes the well-known idiosyncratic volatility (IVOL) puzzle in the stock market (see e.g., Ang, Hodrick, Xing and Zhang (2006) and Bali, Cakici, and Whitelaw (2011)).

Taken together, the findings in this section provide further evidence that option traders with gambling preferences pay attention to implied volatilities and that the *IMPLIED-VOV* has a negative effect on option returns predominately because of gambling behaviors.

5. Conclusion

This paper attempts to explain the negative relation between volatility-of-volatility (VOV) and future delta-hedged option returns. We first show that the three VOV measures constructed from implied and two realized volatility estimates predict option returns in a robust way. To understand the predictability, we explore two potential channels that could drive our results, model risk and gambling preferences. Our empirical analysis confirms both channels but also points out how these channels apply to different VOV measures. Specifically, the gambling-preference channel only applies to the implied VOV measure, while the model-risk channel applies to all three VOV measures.

To further understand the gambling-preference channel, we decompose implied VOV into two semi-variance measures: VOV+ and VOV-, based on volatility-increases and volatility-decreases, respectively. We find a strong negative effect of VOV+ and a weak positive effect of VOV- on option returns. This observation is consistent with the hypotheses that option buyers (writers) with gambling-preference prefer the uncertainty of volatility-increases (decreases), which leads to a higher (lower) option price and a lower (higher) future option return. Moreover, the impact of VOV+ are enhanced by the net option demand from public customers, who are more likely to have gambling preferences. We further document that lottery-like features weaken the effects of VOV+ and VOV- by almost a half. Following the studies of idiosyncratic volatility in the stock market, we document that the negative relation of implied VOV on delta-hedged option returns is driven by its idiosyncratic component.

Several interesting topics are left for future research. Our paper is the first that applies behavioral explanations to the equity option market, where volatility is traded as an asset, echoing and complementing the studies about behavioral explanations for the idiosyncratic volatility puzzle in the stock market. The empirical asset pricing literature has documented a variety of phenomena in the stock market. As the option market rapidly grows, it is may be interesting and plausible to extend these investigations to the option market by studying volatility as a traded asset. Moreover, our paper highlights the pricing impact of volatility trading, which has been documented to be an insignificant determinant of option market activity, compared with speculating on or hedging the direction of underlying stock price movements (Lakonishok, Lee, Pearson, and Poteshman (2007)). It is therefore worth investigating whether the option market trading activity pattern has evolved over time and whether volatility trading has been playing a more important role.

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Appendix: Variable Definitions

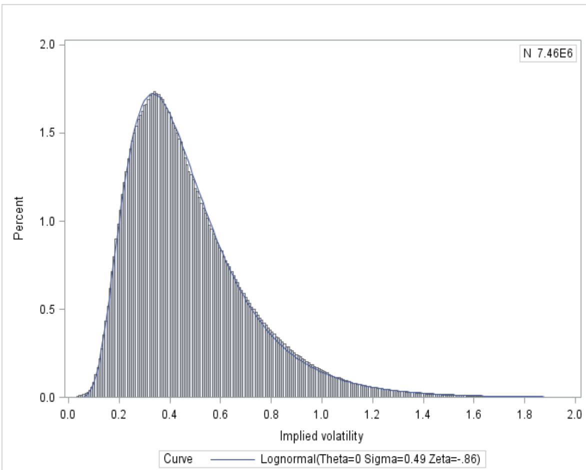
Measures of volatility-of-volatility (VOV)	
IMPLIED-VOV	The standard deviation of the percent change in daily implied volatility with 30 days of maturity over the previous month. We use the at-the-money implied volatility (delta=50) from the Volatility Surface file provided by Option-Metrics.
EGARCH-VOV	The standard deviation of the percent change in daily realized stock volatility over the previous month. Each month for each stock, we estimate the daily realized volatility from an EGARCH (1,1) model using a rolling window of daily returns over the past 12-month period.
INTRADAY-VOV	The standard deviation of the percent change in daily intraday volatility over the previous month. Intraday volatility is calculated using five-minute log return provided by TAQ.
Measures of volatility-of-volatility (VOV): Alternative definition following Baltussen, Van Bekkum, and Van Der Grient (2018)	
IMPLIED-VOV	The standard deviation of the daily at-the-money implied volatility with 30 days to maturity over the previous month, scaled by the average daily implied volatility over the previous month.
EGARCH-VOV	The standard deviation of the daily realized stock volatility over the previous month, scaled by the average daily volatility over the previous month. Each month and for each stock, the daily realized volatility is estimated from an EGARCH (1,1) model using a rolling window of daily returns
INTRADAY-VOV	The standard deviation of the daily intraday volatility over the previous month, scaled by the average daily intraday volatility over the previous month. Intraday volatility is calculated using five-minute log return provided by TAQ.
The decomposition of VOV	
VOV+	The standard deviation of the positive percentage changes of volatility over the previous month.
VOV-	The standard deviation of the negative percentage changes of volatility over the previous month.
Systematic-VOV	The daily percentage change of implied volatility is decomposed into systematic and idiosyncratic components by regressing on the contemporaneous percentage change in market volatility, VIX. *Systematic-VOV* is defined as the exposure to market volatility changes.
Idiosyncratic-VOV	The daily percentage change of implied volatility is decomposed into systematic and idiosyncratic components by regressing on the contemporaneous percentage change in market volatility, VIX. *Idiosyncratic-VOV* is defined as the standard deviation of the idiosyncratic component.

Extreme implied volatility changes as lottery-like features	
IMPLIED-MAX(5)	The average of the highest five daily percentage changes in implied volatility over the previous month.
IMPLIED-MIN(5)	The negative of the average of the lowest five daily percentage changes in implied volatility over the previous month.
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 the option to the midpoint of the bid and ask quotes at the end of the previous month.
Option demand pressure	(Option open interest/stock volume)x10^3. 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.
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 previous 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 as defined in Vasquez (2017).
Variance and Jump measures	
VRP	Volatility 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 from 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 options.
Information 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.
Stock PIN	Probability of informed trading in Easley, Hvidkjaer, and O'hara (2002).

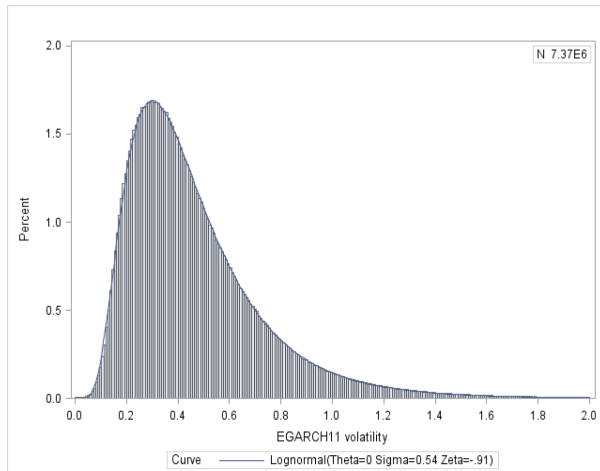
Figure 1. Distribution of daily volatility level and the percentage change of volatility ($\Delta\sigma/\sigma$)

This figure presents the histograms of the daily level and percentage change of the three measures of volatility estimators 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 (d), (e), and (f), respectively.

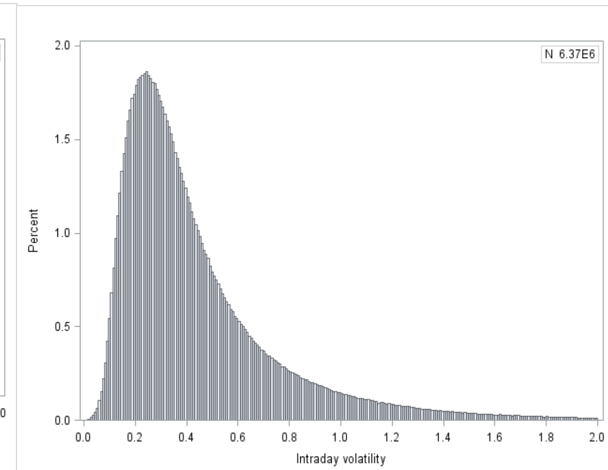
(a) Implied Vol



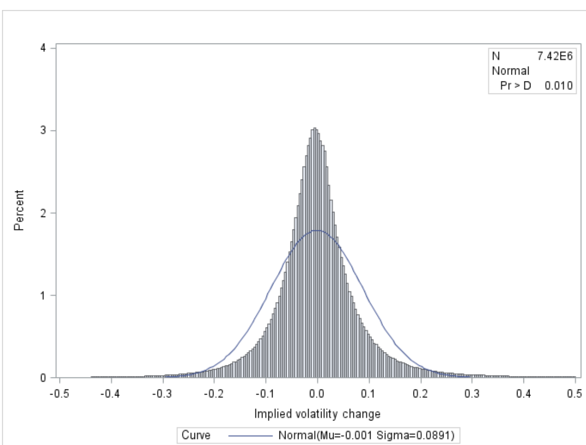
(b) EGARCH Vol



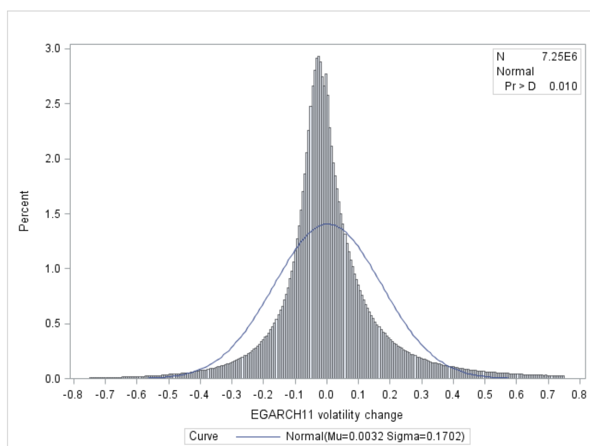
(c) Intraday Vol



(d) Change of Implied Vol



(e) Change of EGARCH Vol



(f) Change of Intraday Vol

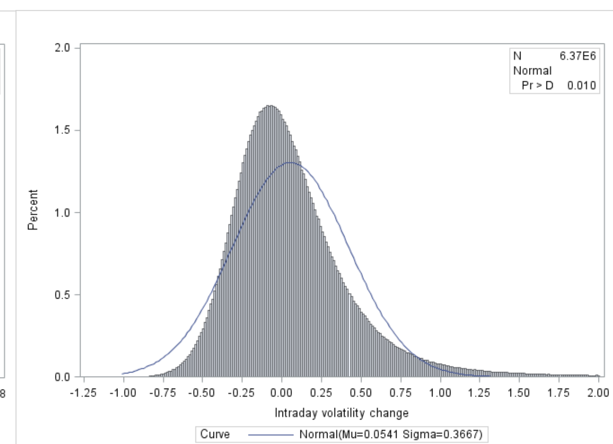


Table 1. Summary Statistics

This table reports descriptive statistics of delta-hedged option returns and volatility-of-volatility (VOV) measrues. The sample period is from January 1996 to April 2016. Panels A.1 and A.2 report call and put option delta-hedged gains over the initial investment, respetivley. The delta-hedged gain is the change over one month or until maturity in the value of a portfolio consisting of one contract of a long call (put) position minus a delta amount on the underlying stock. The delta hedge is rebalanced daily. The initial investment is $(\Delta_c S - C)$ for calls and $(P - \Delta_p S)$ for puts, where Δ is the Black-Scholes option delta, S is the underlying stock price, and C (P) is the call (put) option price. Moneyness is the ratio of the stock to option strike price. Days to maturity is the number of calendar days until the option expiration. Option bid-ask spread is the ratio of the difference between ask and bid quotes of the option to the midpoint of the bid and ask quotes at the end of each month. Panel B.1, B.2, and B.3, report the volatility level σ and VOV, the volatility of the percentage change of volatility $(\Delta\sigma/\sigma)$, in each month for three differerent daily volatility measures. Panel B.1 is based on the daily at-the-money implied volatility (delta=50) from the Volatility Surface file provided by OptionMetrics IvyDB database. Panel B.2 is based on daily volatility estimated using an EGARCH model. Each month and for each stock, the daily realized volatility is estimated from the EGARCH (1,1) model using a rolling window of daily returns over the past 12-month period. Panel B.3 is based on the daily intraday volatility calculated with five-minute log returns provided by TAQ. Panel B.4 reports the correlation matrix of the three VOV measures.

Variables		Mean	Standard deviation	10th percentile	Lower quartile	Median	Upper quartile	90th percentile
Panel A.1 Call options (327,016 observations)								
Delta-hedged gain until month-end / $(\Delta_c S - C)$	(%)	-0.82	4.90	-5.08	-2.66	-0.89	0.75	3.28
Delta-hedged gain until maturity / $(P - \Delta_p S)$	(%)	-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
Quoted option bid-ask spread	(%)	19.29	15.56	5.57	8.80	14.65	24.77	39.19
Panel A.2 Put options (305,710 observations)								
Delta-hedged gain until maturity / $(\Delta_c S - C)$	(%)	-0.48	4.36	-4.33	-2.33	-0.76	0.83	3.36
Delta-hedged gain until month-end / $(P - \Delta_p S)$	(%)	-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
Quoted option bid-ask spread	(%)	20.53	16.36	5.96	9.48	15.61	26.39	41.54
Panel B.1 Based on daily option implied volatility, 324,765 observations								
IMPLIED-Vol level σ		0.48	0.25	0.23	0.30	0.43	0.60	0.80
IMPLIED-VOV (Vol of $\Delta\sigma/\sigma$*)*		0.09	0.08	0.04	0.05	0.07	0.10	0.15
Panel B.2 Based on EGARCH (1,1) daily return volatility, 304,884 observations								
EGARCH-Vol level σ		0.47	0.30	0.20	0.28	0.40	0.58	0.82
EGARCH-VOV (Vol of $\Delta\sigma/\sigma$*)*		0.19	0.23	0.05	0.08	0.13	0.23	0.38
Panel B.3 Based on 5-min intraday return volatility, 277,678 observations								
INTRADAY-Vol level σ		0.45	0.34	0.16	0.23	0.35	0.55	0.86
INTRADAY-VOV (Vol of $\Delta\sigma/\sigma$*)*		0.39	0.20	0.23	0.27	0.35	0.45	0.59

Panel B.4 Correlation matrix of three volatility-of-volatility measures

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

Table 2. Delta-Hedged Option Returns and Volatility-of-Volatility (VOV)

Panel A and B report the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns for call and put options. We use 3 volatility-of-volatility (VOV) measures. *IMPLIED-VOV* is calculated using daily at-the-money implied volatility (delta=50) from the Volatility Surface file provided by OptionMetrics IvyDB database. *EGARCH-VOV* is calculated based on daily volatility estimated using an EGARCH model. Each month and for each stock, the daily realized volatility is estimated from the EGARCH (1,1) model using a rolling window of daily returns over the past 12 months. *INTRADAY-VOV* is calculated using daily intraday volatility calculated with five-minute returns from TAQ database. VOV is defined as the standard deviation of percentage change of volatility ($\Delta\sigma/\sigma$) in each month. Panel A reports the delta-hedged gain until month-end over ($\Delta_c S - C$) for call and ($P - \Delta_p S$) for put. Panel B reports four definitions of option returns: (1) delta-hedged gain until month-end / stock price, (2) delta-hedged gain until month-end/option price, (3) delta-hedged gain until maturity, and (4) delta-hedged gain until week-end. All independent variables are winsorized each month at the 0.5% level. Panel C reports average portfolio returns for quintile portfolios ranked by four measures of volatility-of-volatility (VOV): *IMPLIED-VOV*, *EGARCH-VOV*, *INTRADAY-VOV*, and *Combined-VOV*. The Combined VOV is computed as the average of the ranking percentile of the 3 individual VOV measures. We report average delta-neutral call writing returns with equal weighting (EW) and open interest weighting (OW) which weights by the market value of the option open interest. We report the average return to delta-neutral call writing for each quintile portfolio, and both the raw and risk-adjusted return spread that longs quintile 5 and shorts quintile 1. The 3-factor, 5-factor, and 7-factor alphas are derived from the Fama-French 3-factor model, the 5-factor model which adds momentum and the zero-beta straddle return of the S&P 500 Index option from Coval and Shumway (2001), and the 7-factor model which adds the change in VIX and the Kelly and Jiang (2014) tail risk factor. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

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

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

Panel B. Alternative dependent variables

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

Panel C. Portfolio returns sorted on VOV (%)

Sorted on	Weight	Q1	Q2	Q3	Q4	Q5	(5 -1) Raw Return	3-factor Alpha	5-factor Alpha	7-factor Alpha
IMPLIED-VOV	EW	0.89	1.09	1.26	1.54	1.77	0.88***	0.88***	0.92***	0.89***
		(6.39)	(8.76)	(9.95)	(12.49)	(14.21)	(13.77)	(13.64)	(12.18)	(11.62)
	OW	0.93	1.12	1.31	1.63	1.97	1.04***	1.04***	1.09***	1.07***
		(6.84)	(9.21)	(10.61)	(13.28)	(15.80)	(13.38)	(12.99)	(11.47)	(10.16)
EGARCH-VOV	EW	1.15	1.16	1.25	1.38	1.68	0.52***	0.54***	0.56***	0.59***
		(8.48)	(9.28)	(10.27)	(10.92)	(13.62)	(10.46)	(10.16)	(8.43)	(7.00)
	OW	1.16	1.18	1.30	1.42	1.73	0.57***	0.58***	0.60***	0.64***
		(8.67)	(9.53)	(10.93)	(11.85)	(14.08)	(9.95)	(9.54)	(7.82)	(6.67)
INTRADAY-VOV	EW	1.08	1.12	1.21	1.30	1.56	0.47***	0.47***	0.48***	0.38***
		(8.63)	(8.34)	(8.47)	(9.16)	(9.98)	(5.28)	(5.15)	(4.58)	(3.01)
	OW	1.12	1.18	1.27	1.36	1.65	0.54***	0.52***	0.52***	0.45***
		(9.34)	(8.88)	(8.84)	(9.80)	(11.34)	(6.35)	(6.02)	(4.94)	(3.50)
Combined-VOV	EW	0.85	1.04	1.20	1.39	1.77	0.92***	0.92***	0.91***	0.90***
		(6.07)	(7.49)	(9.56)	(9.42)	(12.51)	(15.62)	(14.67)	(11.37)	(11.31)
	OW	0.89	1.09	1.27	1.46	1.96	1.06***	1.06***	1.07***	1.08***
		(6.47)	(8.05)	(10.45)	(9.98)	(14.51)	(15.03)	(14.10)	(11.48)	(11.29)

Table 3. Volatility-of-Volatility and Option Demand Pressure

This table reports the average coefficients from monthly Fama-MacBeth regressions. Panel A reports regression results of demand pressure of call options on contemporaneous VOV measures. Panel B reports regression results of VOV on delta-hedged option returns until month-end for call options after controlling for option demand pressure. *IMPLIED-VOV*, *EGARCH-VOV* and *INTRADAY-VOV* are calculated using three measures of volatility as described in Table 2. VOV is defined as the standard deviation of the percentage change in volatility in the previous month. Option demand pressure is calculated as (Option open interest/stock volume)x10^3. Option open interest is the total number of option contracts that are open at the end of the previous month. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Panel A. Option demand pressure and contemporaneous VOV measures

Fama-MacBeth Regressions	Call Options			
	Option Demand Pressure			
IMPLIED-VOV	0.026***			0.023***
	(4.26)			(3.76)
EGARCH-VOV		-0.005***		-0.002**
		(-3.91)		(-2.05)
INTRADAY-VOV			-0.013***	-0.013***
			(-4.74)	(-4.77)
Intercept	0.028***	0.030***	0.033***	0.031***
	(23.16)	(26.02)	(22.57)	(20.47)
Adj. R^2	0.001	0.001	0.001	0.002

Panel B. Controlling for option demand pressure

Fama-MacBeth Regressions	Call Options			
	Delta-hedged gain until month-end/($\Delta_c S - C$)			
IMPLIED-VOV	-2.330***			-2.201***
	(-5.86)			(-5.35)
EGARCH-VOV		-0.706***		-0.626***
		(-8.55)		(-6.42)
INTRADAY-VOV			-0.958***	-0.847***
			(-6.16)	(-5.37)
Demand Pressure	-2.462***	-2.505***	-2.590***	-2.538***
	(-9.49)	(-9.58)	(-8.45)	(-8.61)
Intercept	-0.549***	-0.587***	-0.331**	-0.111
	(-4.56)	(-4.85)	(-2.46)	(-0.80)
Adj. R^2	0.006	0.005	0.006	0.011

Table 4. Volatility of Volatility-Increases vs. Volatility of Volatility-Decreases

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until the month-end for call options. $VOV+$ is defined as the volatility of positive volatility percentage changes and VOV- is defined as the volatility of negative volatility percentage changes in the past month. Panels A and B show univariate regression results of $VOV+$ and VOV-, respectively. Panel C shows bivariate regression results of $VOV+$ and VOV-. Panel D reports the results of multivariate regressions in which we further interact $VOV+$ and VOV- with the option order imbalance from public customers (*OOI*). We report in brackets Newey-West (1987) t-statistics.

Dependent Variable:
Delta-hedged gain until month-end/($\Delta_c S - C$)

Panel A. $VOV+$

	IMPLIED	EGARCH	INTRADAY
$VOV+$	-4.197***	-0.449***	-0.794***
	(-7.69)	(-5.82)	(-5.09)
Intercept	-0.600***	-0.727***	-0.573***
	(-4.81)	(-5.87)	(-5.10)
Adj. R^2	0.005	0.001	0.003

Panel B. VOV-

	IMPLIED	EGARCH	INTRADAY
VOV-	0.211	-3.115***	-4.302***
	(0.26)	(-9.50)	(-8.11)
Intercept	-0.813***	-0.572***	-0.184
	(-6.51)	(-4.45)	(-1.29)
Adj. R^2	0.002	0.002	0.003

Panel C. *VOV+* and *VOV-*			
	IMPLIED	EGARCH	INTRADAY
VOV+	-6.896***	-0.288***	-0.514***
	(-8.58)	(-4.04)	(-3.68)
VOV-	8.351***	-2.399***	-3.132***
	(6.79)	(-7.98)	(-7.47)
Intercept	-0.815***	-0.583***	-0.208
	(-6.49)	(-4.56)	(-1.45)
Adj. R^2	0.006	0.003	0.005

Panel D.
VOV+, VOV-, and option order imbalance (*OOI*) from public customers

	IMPLIED	EGARCH	INTRADAY
VOV+	-5.203***	-0.305**	-0.886***
	(-5.45)	(-2.51)	(-3.05)
(VOV+) x *OOI*	-0.106***	0.002	-0.008
	(-2.81)	(0.35)	(-1.31)
VOV-	3.615**	-2.342***	-4.260***
	(2.58)	(-5.05)	(-6.68)
(VOV-) x *OOI*	0.022	-0.024	0.007
	(0.70)	(-1.18)	(0.26)
OOI	0.001	-0.000	0.001
	(0.72)	(-0.02)	(0.15)
Intercept	-0.722***	-0.558***	0.050
	(-4.58)	(-3.43)	(0.24)
Adj. R^2	0.007	0.006	0.007

Table 5. Extreme Changes in Implied Volatility as the Lottery-Like Features

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until the month-end for call options. *IMPLIED-VOV+* is defined as the volatility of positive implied volatility percentage changes and *IMPLIED-VOV-* is defined as the volatility of negative implied volatility percentage changes in the past month. Following Bali, Cakici, and Whitelaw (2011), *IMPLIED-MAX(5)* is defined as the average of the highest (lowest) five daily percentage changes in implied volatility over the previous month. *IMPLIED-MIN(5)* is defined as the negative of the average of the lowest five daily percentage changes in implied volatility over the previous month. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Fama-MacBeth	Call Options		
Regressions	Delta-hedged gain until month-end/$(\Delta_c S - C)$		
IMPLIED-VOV+	-6.896***		-3.785***
	(-8.58)		(-5.30)
IMPLIED-VOV-	8.351***		4.738***
	(6.79)		(4.78)
IMPLIED-MAX(5)		-8.046***	-6.997***
		(-9.33)	(-9.04)
IMPLIED-MIN(5)		9.468***	8.925***
		(-9.48)	(-8.55)
Intercept	-0.815***	-0.814***	-0.866***
	(-6.49)	(-6.37)	(-6.89)
Adj. R^2	0.006	0.009	0.014

Table 6. The Decomposition of Implied Volatility Changes: Systematic-VOV vs. Idiosyncratic-VOV

In this table, we decompose the daily percentage change in implied volatility by using the implied volatility of each stock, σ_t, and the VIX index, σ_{mt}. Every month, we then run the following regression for each stock using daily data: $\frac{\Delta\sigma_t}{\sigma_t} = \alpha + \beta\frac{\Delta\sigma_{mt}}{\sigma_{mt}} + \epsilon_t$. *Systematic-VOV* is measured by β, the systematic exposure to the percentage change of σ_{mt} (*Beta to (%Δ in MKT Vol)*). *Idiosyncratic-VOV* is measured as the standard deviation of ϵ_t, *Vol of (idio %Δ in Vol).* All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Systematic-VOV vs. *Idiosyncratic-VOV*

	(1)	(2)	(3)	(4)
IMPLIED-VOV	-3.555***			
	(-7.24)			
Systematic-VOV:		0.175**		0.203***
Beta to (%Δ in MKT Vol)		(2.43)		(2.85)
Idiosyncratic-VOV:			-2.508***	-2.702***
Vol of (Idio %Δ in Vol)			(-6.18)	(-6.95)
Intercept	-0.429***	-0.835***	-0.588***	-0.649***
	(-3.14)	(-7.63)	(-4.94)	(-5.60)
Adj. R^2	0.006	0.004	0.007	0.004

Internet Appendix:

Why does Volatility Uncertainty Predict Equity Option Returns?

In the Internet Appendix, we study whether the effect of volatility-of-volatility (VOV) is robust to alternative definitions or whether it could be explained by different sets of control variables. For these tests, we mainly focus on call options. The results for put options are similar to those for call options and are available upon request.

1. The alternative definition of VOV measures

In Baltussen, Van Bekkum, and Van Der Grient (2018), the VOV measure is defined as the standard deviation of the daily volatility level over the previous month, scaled by the average daily volatility level over the previous month. Using this alterantive VOV definition does not change the results as reported in the Appendix Table A1.

2. Control for volatility related measures

The negative VOV effect might be explained by the volatility level and several other volatility-related measures that predict future delta-hedged option returns. Specifically, higher levels of VOV might be the result of market frictions, investors' overreaction or inaccurate estimation of volatility. In Panel A of Appendix Table A2 we control for three volatility-related variables. The first variable is ImpliedVol, the average of ATM implied volatility of call and put options. The second variable is VOL_deviation defined as the log difference between realized volatility and the Black-Scholes implied volatility for ATM options at the end of the previous month. Realized volatility is the annualized standard deviation of stock returns estimated from daily data over the previous month. Goyal and Saretto (2009) conclude that the significant negative relation of VOL_deviation and delta-hedged option returns is consistent with mean reversion of volatility and with investors' overreaction. The third variable is the VTS slope, defined as the difference between the long-term and short-term volatility in Vasquez (2017). Vasquez (2017) finds that VTS slope is a strong predictor variable of the future straddle returns of individual stocks because of investor overreaction and underreaction.

Panel A of Appendix Table A2 shows that the three VOV variables remain negative and significant after controlling for volatility measures that predict option returns. Overall, the result suggests that our documented impact of VOV on the cross-sectional delta-hedged option returns cannot be explained by volatility-related mispricing or frictions of financial intermediaries documented in the previous literature. In Panel B of Table A2, we control for IVOL instead of ImpliedVol, the annualized stock return idiosyncratic volatility defined in Ang, Hodrick, Xing and Zhang (2006) and Cao and Han (2013) and obtain similar results.

3. Control for volatility risk premium

Another possibility is that our documented effects come from the relation between VOV and the volatility risk premium (VRP). Previous studies (e.g., Bakshi and Kapadia (2003); Bakshi and Kapadia (2003) show that delta-hedged option gains are related to the VRP. Bollerslev, Tauchen, and Zhou (2009) show, in an extended long-run risk model, that VRP at the index level is proportional to the time varying volatility-of-volatility. Consequently, VOV and future delta-hedged option returns are potentially linked through VRP.

While the source and significance of individual stock VRP are still not well understood, they can be empirically estimated (see e.g., Carr and Wu (2009) and Han and Zhou (2015)) and theoretically related to the expected delta-hedged option gains under a stochastic volatility model (e.g., Bakshi and Kapadia (2003)). We compute the VRP as the difference between realized and implied volatilities 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 realized counterpart is proxied by realized variance computed from high-frequency returns over the given month. We now examine whether our results can be explained by the relation between individual VRP and VOV measures.

In Table A2 Panel C, we include individual VRP along with the VOV measures in Fama-MacBeth regressions. The individual stock VRP in all regressions has a significantly positive coefficient consistent with the findings in previous literature. More importantly, after controlling for VRP, the coefficients for the three VOV measures remain negative and significant at the 1% level. Therefore, individual stock VRP does not explain the significant empirical relation between delta-hedged option returns and VOV.

4. Control for jump risk

As argued by Green and Figlewski (1999), option dealers may charge a premium for jump risk when they write options. The negative VOV effect on option returns might potentially reflect a compensation for jump risk. Firms with higher uncertainty in volatility may experience sudden stock price jumps, either positive or negative.

To address the concern that the effect of VOV is explained by the jump risk of individual stocks, we consider three sets of jump measures. The first set contains the model-free left and right jump tail measures calculated from option prices according to Bolleslev and Todorov (2011). The second jump risk variable is risk-neutral skewness given that jump risk manifests itself in implied skewness when it deviates from zero. The risk-neutral skewness of stock returns is inferred from a portfolio of options across different strike prices following Bakshi, Kapadia, and Madan (2003). Since the calculation of implied skewness requires at least two out-of-the-money call options and two out-of-the-money put options the sample is reduced to about one third of the original sample. The third variable is the volatility spread defined as the spread of implied volatility between ATM call and put options according to Bali and Hovakimian (2009) and Yan (2011).

Panel D of Table A2 reports the Fama-MacBeth regression results when controlling for jump risk. The coefficients of the left and right jump tail measures are both negative and significant, indicating that higher jump risk predicts lower delta-hedged option returns, irrespective of the direction of the jump. The coefficients of implied skewness and volatility spread are also significant in all regressions while the coefficients of the VOV measures remain economically large and significant. Overall, jump risk does not explain the negative relation between VOV measures and option returns.

5. Control for liquidity measures

Liquidity of the option market have been shown to impact option prices. For example, Christoffersen, Goyenko, Jacobs, and Karoui (2018) document a significant illiquidity premium in equity option markets. Options with high VOV could be those with high illiquidity, and, hence they yield lower returns.

To measure illiquidity, we use three variables: stock illiquidity, option bid-ask spread and the total size of all calls. Stock illiquidity is proxied with the Amihud measure and option illiquidity is proxied with the option bid-ask spread. Amihud is calculated as the average of the daily Amihud (2002) illiquidity measure over the previous month. Option bid-ask spread is the ratio of the difference between the bid and ask quotes of the option to the midpoint of the bid and ask quotes at the end of previous month. The total size of all calls is the logarithm of the total market value of the open interest of all call options.[23]

Appendix Table A3 reports the Fama-MacBeth regression results of the delta-hedged option returns on VOV measures when controlling for illiquidity. We confirm the results in Christoffersen, Goyenko, Jacobs, and Karoui (2018) that the higher the option illiquidity, the lower the expected option returns. More importantly, the three VOV variables remain negative and significant after controlling for illiquidity.

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[23] 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.

6. Control for stock information uncertainty and asymmetry

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

Appendix Table A4 shows the results of Fama-MacBeth cross-sectional regressions when controlling for information uncertainty and information asymmetry. Consistent with the channel of information risk, the result suggests that the lower the analysis coverage and the higher the dispersion, the lower the future delta-hedged option returns are. The negative VOV effect remains significant after controlling for the information uncertainty and asymmetry measures. The results indicate that the effect of VOV is robust after controlling for measures of uncertainty.

Table A1. Delta-Hedged Option Returns and Volatility-of-Volatility (Alternative Definition)

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month's end for both call options and put options. The calculation of the alternative VOV measures follows Baltussen, Van Bekkum, and Van Der Grient (2018). VOV is defined as the standard deviation of volatility scaled by the average of volatility in each month. *IMPLIED-VOV* is calculated using daily at-the-money implied volatility (delta=50) from the Volatility Surface file provided by the OptionMetrics IvyDB database. *EGARCH-VOV* is calculated based on daily volatility estimated using an EGARCH model. Each month and for each stock, the daily realized volatility is estimated from an EGARCH (1,1) model using a rolling window of daily returns over the past 12-month period. *INTRADAY-VOV* is calculated using daily intraday volatility calculated with five-minute log returns provided by TAQ. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. To adjust for serial correlation, robust Newey-West (1987) t-statistics are reported in brackets.

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

Table A2. Control for Volatility-Related Measures, Volatility Risk Premium, and Jump Risk

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month-end for call options. *IMPLIED-VOV*, *EGARCH-VOV*, and *INTRADAY-VOV* are calculated using three measures of volatility as described in Table 2. VOV is defined as standard deviation of the percentage change in volatility in the previous month. *ImpliedVol* is the average of at-the-money implied volatility of call and put options. *VOL_deviation* is the log difference between the realized volatility and the Black-Scholes implied volatility for at-the-money options at the end of last month as in Goyal and Saretto (2009). Realized volatility is the standard deviation of stock returns estimated from daily data over the previous month. *VTS slope* is the difference between the long-term and short-term volatility defined in Vasquez (2017). Idiosyncratic volatility (*IVOL*) is defined as the annualized stock return idiosyncratic volatility defined in Ang, Hodrick, Xing, and Zhang (2006). The volatility risk premium (*VRP*) is defined as the difference between the square root of realized variance estimated from intraday stock returns over the previous month and the square root of a model free estimate of the risk-neutral volatility. *Jump_left* (*Jump_right*) is the model-free left/right jump tail measure calculated with option prices defined in Bolleslev and Todorov (2011). *Implied skewness* is the risk-neutral skewness of stock returns as in Bakshi, Kapadia, and Madan (2003). *Volatility spread* is the implied volatility difference between ATM call and put options. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Panel A: Control for volatility-related measures

Fama-MacBeth Regressions	Call Options			
	Delta-hedged gain until month-end/($\Delta_c S$– C)			
IMPLIED-VOV	-1.644***			-1.915***
	(-3.98)			(-4.12)
EGARCH-VOV		-0.769***		-0.710***
		(-7.57)		(-6.68)
INTRADAY-VOV			-0.744***	-0.660***
			(-5.34)	(-4.92)
ImpliedVol	-4.678***	-4.643***	-4.548***	-4.466***
	(-20.97)	(-20.98)	(-19.55)	(-18.98)
VOL_deviation	2.088***	2.177***	2.045***	2.158***
	(10.92)	(11.44)	(10.69)	(10.78)
VTS slope	3.264***	3.280***	3.282***	3.140***
	(8.65)	(8.67)	(8.25)	(7.98)
Intercept	1.689***	1.724***	1.802***	1.985***
	(15.13)	(16.92)	(18.26)	(17.67)
Adj. R^2	0.107	0.107	0.105	0.110

Panel B: Control for idiosyncratic volatility of stock return

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

Table A2 (Continued)

Panel C: Control for volatility risk premium

Fama-MacBeth Regressions	Call Options			
	Delta-hedged gain until month-end/($\Delta_c S$− C)			
IMPLIED-VOV	-1.265***			-1.330***
	(-2.88)			(-2.95)
EGARCH-VOV		-0.350***		-0.294***
		(-4.04)		(-3.43)
INTRADAY-VOV			-0.707***	-0.669***
			(-4.72)	(-4.42)
ImpliedVol	-4.846***	-4.856***	-4.591***	-4.518***
	(-21.45)	(-21.67)	(-21.20)	(-20.78)
VRP	3.476***	3.481***	3.729***	3.826***
	(11.42)	(11.61)	(11.82)	(12.10)
Intercept	1.781***	1.782***	1.916***	1.999***
	(13.72)	(14.55)	(16.51)	(16.17)
Adj. R^2	0.094	0.092	0.094	0.097

Panel D: Control for jump risk

IMPLIED-VOV	-1.014***			-0.944**
	(-2.33)			(-2.31)
EGARCH-VOV		-0.270***		-0.178*
		(-2.69)		(-1.77)
INTRADAY-VOV			-0.620***	-0.563***
			(-4.33)	(-3.97)
ImpliedVol	-2.882***	-2.864***	-2.582***	-2.694***
	(-6.03)	(-6.01)	(-5.27)	(-5.40)
Jump_left	-1.157***	-1.238***	-1.348***	-1.310***
	(-3.77)	(-4.04)	(-4.15)	(-4.06)
Jump_right	-0.591*	-0.519*	-0.543*	-0.488
	(-1.94)	(-1.70)	(-1.80)	(-1.57)
Implied skewness	-0.020	-0.017	-0.020	-0.021
	(-1.24)	(-1.02)	(-1.18)	(-1.26)
Volatility spread	9.246***	9.210***	9.513***	9.567***
	(16.39)	(16.33)	(18.09)	(18.10)
Intercept	0.977***	0.965***	1.069***	1.163***
	(5.11)	(5.17)	(5.69)	(5.80)
Adj. R^2	0.101	0.102	0.102	0.105

Table A3. Control for Liquidity Measures

This table reports the average coefficients from monthly Fama-MacBeth regressions of delta-hedged option returns until month-end for call options. *IMPLIED-VOV*, *EGARCH-VOV*, and *INTRADAY-VOV* are calculated using three measures of volatility as described in Table 2. VOV is defined as the standard deviation of the 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 the option to the midpoint of the bid and ask quotes at the end of the 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. *Ln(total size of all Calls)* is the log of the total market value of the open interest of all call options in the previous month. All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Fama-MacBeth Regressions	Call Options			
	Delta-hedged gain until month-end/($\Delta_c S - C$)			
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)
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 A4. 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 call options. *IMPLIED-VOV*, *EGARCH-VOV*, and *INTRADAY-VOV* are calculated using three measures of volatility as described in Table 2. VOV is defined as the 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. *Stock PIN* is the probability of informed trading in Easley, Hvidkjaer, and O'hara (2002). All independent variables are winsorized each month at the 0.5% level. The sample period is from January 1996 to April 2016. We report in brackets Newey-West (1987) t-statistics.

Fama-MacBeth	Call Options			
Regressions	Delta-hedged gain until month-end/($\Delta_c S - C$)			
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

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