Jumps and the Correlation Risk Premium: Evidence from Equity Options

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Abstract

This paper breaks the correlation risk premium down into two components: a premium related to the correlation of continuous stock price movements and a premium for bearing the risk of co-jumps. We propose a novel way to identify both premiums based on a dispersion trading strategy that goes long an index option portfolio and short a basket of option portfolios on the constituents. The option portfolios are constructed to only load on either diffusive volatility or jump risk. We document that both risk premiums are economically and statistically significant for the S&P 100 index. In particular, selling insurance against states of high jump correlation generates a sizable annualized Sharpe ratio of 0.85.

Keywords: Correlation Risk · Option-Implied Information · Variance Risk Premium

JEL: G12 · G13

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Abstract

This paper breaks the correlation risk premium down into two components: a premium related to the correlation of continuous stock price movements and a premium for bearing the risk of co-jumps. We propose a novel way to identify both premiums based on a dispersion trading strategy that goes long an index option portfolio and short a basket of option portfolios on the constituents. The option portfolios are constructed to only load on either diffusive volatility or jump risk. We document that both risk premiums are economically and statistically significant for the S&P 100 index. In particular, selling insurance against states of high jump correlation generates a sizable annualized Sharpe ratio of 0.85.

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1 Introduction

Investors fear stock market turbulence. They want to hedge against states of high volatility and are willing to pay a large premium for such insurance, known as the market variance risk premium (VRP). When markets are turbulent, investors reduce their exposure and flee risky stocks. This collective behavior causes stocks to fall in harmony and losses to spiral. In other words, stock correlations go up and diversification benefits vanish when needed most. In order to eliminate the risk of high correlations, investors pay the so-called correlation risk premium (CRP). There is a close theoretical link between the two risk premiums: The market VRP can be expressed as the sum of the CRP and the individual VRPs of single stocks.

Previous research has focussed on assessing the size and predictive power of the risk premiums. As summarized by Zhou (2018), empirical studies agree on the notion that the market VRP is economically and statistically significant and predicts future market returns at few-month horizons. Driessen et al. (2009) document that the CRP for the S&P 100 index is sizable. In addition, Buss et al. (2018) provide evidence that the CRP predicts future market returns at horizons of up to one year. Individual VRPs are examined by Carr and Wu (2009). They show that individual VRPs have a large cross-sectional variation and, in particular, find that only few stocks generate statistically significant VRPs. In conclusion, previous research implies that the CRP is the key determinant of the market VRP.

Despite the importance of the CRP, little is known about its drivers so far. Stocks may be correlated because they continuously move in the same direction or because they experience co-jumps, i.e. common discontinuous movements on rare occasions. Depending on the origin, investors may be willing to pay very different premiums to hedge against states of high correlations. Hypothetically, co-jumps may pose a greater threat to investors and therefore carry a higher premium. This question is natural to ask given that Bollerslev and Todorov (2011) show that a large fraction of the market VRP is actually attributable to the compensation for jump risks rather than diffusive volatility risks.

This paper fills the gap by breaking the CRP down into two components: a premium related to the correlation of continuous stock price movements and a premium for bearing the risk of co-jumps. We build on Cremers et al. (2015) and construct option portfolios that only load on diffusive innovations (or jumps, respectively) of the underlying. A dispersion trade in these portfolios for the index and the constituent stocks gives portfolios with an exposure to the correlation of the diffusive changes (co-jumps) only. The excess returns of these portfolios then allow us to assess the pricing of correlation risk. We apply this methodology to the S&P 100 index and find that both types of correlation carry significant risk premiums. The premium for the correlation of co-jumps, however, is much larger than the premium for the correlation of continuous stock price movements.

The VRP is the difference between the expectations of the realized variance under the physical measure and the risk-neutral measure. Based on the relation between the variance of the index and the variances of the constituent stocks, we first show in the theoretical part that the VRP of the index depends on the average VRP of the single stocks, but also on the correlation of the stocks and the CRP. If the VRP of the single stocks is on average equal to zero, the VRP of the index arises due to the CRP. Investor then pay a premium to insure against the risk of an increasing correlation and thus the risk of worsening diversification in the market.

In order to identify the premia for variance risk and correlation risk, we rely on options. The basic idea is that the excess return of an option depends on the premia paid for diffusive changes in the underlying, jumps in the underlying, and changes in the variance. We then set up portfolios which isolate the premia for the correlation of the diffusive changes in stock prices and the premia for the correlation of jumps. Note that option returns contain all the necessary information and directly load on the premia. Different from the standard approach to assess the risk premia, we thus do not have to determine the expectations of the realized variance under the physical and risk-neutral measure separately. As a result, our approach has the advantage that it does not rely on high-frequency data.

In the empirical part, we follow Cremers et al. (2015) and set up portfolios which are only exposed to changes in the diffusive variance (VOL portfolio) and jumps in the underlying ($JUMP$ portfolio). In a next step, we combine the resulting portfolios for the index and the constituents in a dispersion trade similar to Driessen et al. (2009), such that they are only exposed to the correlation of diffusive stock price changes (CRP_{VOL} portfolio) and to the correlation of jumps (CRP_{JUMP} portfolio). The expected excess returns of these portfolios then tell us something about the pricing of the different origins of correlations. Our analysis focuses on the S&P 100 index and its constituents within the sample period from January 1996 to December 2017. For the index, it holds that the VRP is significantly negative. For the single stocks, we find large cross-sectional differences in the VRP, with both significantly positive and significantly negative VRPs. On average, however, the individual VRPs of single stocks are close to zero. The VRP of the index can thus not be attributed to the VRPs of the constituent stocks, but rather represents a premium for correlation risk. Studying the excess returns of the CRP_{VOL} portfolio, we find a significantly negative risk premium for the correlation of diffusive stock price changes. The Sharpe ratio amounts to 0.45 per year. Furthermore, the excess returns of the CRP_{JUMP} portfolio imply a large negative premium associated with the risk of co-jumps. The annualized Sharpe ratio amounts to 0.85 and is thus almost twice as large as the one for the CRP_{VOL} portfolio.

Our paper is related to several strands of the literature. First, we build on the literature on variance risk and the VRP. Drechsler and Yaron (2011) study the variance risk premium in a long-run risk model where it can mainly be attributed to stock price jumps. Second, we add to the literature on correlation risk and the CRP. Driessen et al. (2009) show how to determine the price of correlation risk from option portfolios via dispersion trades. Faria et al. (2018) examine the CRP in several countries and document that there is a global correlation risk factor related to economic uncertainty. Hollstein and Simen (2018) compare the variance risk premium of the index to the variance risk premiums in the cross section of stocks. They argue that the level of the index VRP is mainly driven by the CRP, whereas the variation of the index VRP comes from the individual VRPs. Buss et al. (2017) find that the CRP has predictive power for future index returns up to a one-year horizon, while the implied correlation predicts the future dispersion of stock betas and the future realized correlation. Finally, we relate to literature using option returns to measure risk premia. Bakshi and Kapadia (2003) use delta-hedged option portfolio returns and show that the variance risk premium of the market is negative on average. Looking separately at jump and diffusive market risks, Cremers et al. (2015) use option straddles to construct portfolios that load either on volatility risk or on jump risk. They show that investors are willing to pay a premium to hedge both kinds of risks and, furthermore, provide evidence that both risks are priced in the cross-section of stock returns. Finally, Middelhoff (2018) extends the method of Cremers et al. (2015) by imposing a constant sensitivity towards jump and volatility risk and thereby makes option returns on the index as well as on single stocks comparable. However, he concentrates on market and idiosyncratic risks, only, and ignores the effects of correlation risk among stocks.

The remainder of this paper is organized as follows. In Section 2, we relate the VRP of the index to the VRPs of the constituent stocks and the CRP, and we show how to construct the option portfolios that allow to trade correlation risk. In Section 3 we analyze the pricing of correlation risk for the S&P 100 index. Section 4 concludes. All proofs are in the Appendix.

2 Theoretical Framework

In this section, we analyse the components of the VRP of the index. We first show in general that the VRP of the index depends on the average VRP of the constituent stocks and the CRP. From this general relation, we can conclude that the VRP of the index can exceed the VRP of its constituents if the CRP is large enough.

For a more detailed analysis and a decomposition of the CRP into a diffusive and a jump part, we assume that the stocks follow jump-diffusion processes with stochastic variances. It is then possible to set up delta-gamma-neutral portfolios to trade variance innovations, and delta-vega-neutral portfolios to trade jump risk. Combining a long position in these portfolios for the index with short positions in these portfolios for the constituents allows to isolate the payoffs from exposures to the correlation of diffusive stock innovations and exposures to co-jumps of the stocks.

2.1 Index VRP and CRP

The variance of the index is the sum of the variances and covariances of the single stocks:

$$Var_t\left(\frac{S_{I,T}}{S_{I,t}}\right) = \sum_{i=1}^{N}\omega_i^2 Var_t\left(\frac{S_{i,T}}{S_{i,t}}\right) + \sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}\omega_i\omega_j\sigma_t\left(\frac{dS_{i,T}}{S_{i,t}}\right)\sigma_t\left(\frac{S_{j,T}}{S_{j,t}}\right)\rho_{ij,t}$$

where Var and σ denote the variances and volatilities, and where ρ_{ij} is the correlation between stocks i and j. ω_i is the percentage weight of stock i in the index. With N variance terms and $N(N-1)$ covariance terms, it is mainly the sum of the covariances which determines the variance of the index.

The covariances depend on volatilities and correlations. Given the volatilities of the single stocks, the variance of the index is thus mainly determined by the correlations. In the literature, one often considers the equi-correlation ρ instead of the $N(N-1)/2$ pairwise correlations ρ_{ij} to describe the joint movements of the single stocks.

The VRP is defined as the difference between the physical and the risk-neutral expectation of realized variance. For the index, this VRP is negative, i.e. investors are willing to pay a premium in order to insure themselves against an increase of variance.

The VRP of the index depends on the VRP of the single stocks and on the covariance risk premium $CovRP$:

$$VRP_I = \sum_{i=1}^{N} \omega_i^2 VRP_i + \sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} \omega_i \omega_j CovRP_{ij}$$

Again, the covariance risk premiums are more important than the variance risk premiums. They are given by

$$\begin{aligned} CovRP_{ij} &= \sqrt{V_i}\sqrt{V_j}\rho_{ij} - \sqrt{V_i - VRP_i}\sqrt{V_j - VRP_j}(\rho_{ij} - CorrRP_{ij}) \\ &\approx 0.5\,(VRP_i + VRP_j)\,\rho_{ij} + \sqrt{V_i}\sqrt{V_j}CorrRP_{ij} - 0.5\,(VRP_i + VRP_j)\,CorrRP_{ij} \end{aligned}$$

The VRP of the index is thus approximately given by

$$VRP_I \approx \overline{VRP}_{stock}\ \rho + \overline{Var}_{stock} CorrRP - \overline{VRP}_{stock} CorrRP.$$

It depends on the average VRP of the stocks (multiplied by the equicorrelation), the CRP (multiplied by the average variance), and the product of both risk premiums. For the (negative) VRP of the index to exceed the average VRP of the single stocks in absolute terms, we need approximately that the following inequality holds true:

$$CorrRP \leq (1 - \rho) \frac{\overline{VRP}_{stock}}{\overline{Var}_{stock} - \overline{VRP}_{stock}}$$

The CRP thus has to be sufficiently negative, i.e. the correlation under the risk-neutral measure has to be higher than the historical correlation.

2.2 Option Portfolios

The dynamics of stock i are given by

$$\begin{aligned}\frac{dS_{i,t}}{S_{i,t-}} &= \mu_i dt + \sqrt{V_{i,t}}dW_t^{Si} + \frac{\Delta S_{i,t}}{S_{i,t-}}\\ dV_{i,t} &= \mu_{Vi}dt + \sigma_{Vi}\sqrt{V_{i,t}}dW_t^{Vi} + \Delta V_{i,t}.\end{aligned}$$

The index and its local variance are equal to

$$\begin{aligned}S_{I,t} &= \sum_{i=1}^{N} w_i S_{i,t}\\ V_{I,t} &= \sum_{i=1}^{N} \omega_i^2 V_{i,t} + \sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N} \omega_i\omega_j\sqrt{V_{i,t}V_{j,t}}\rho_t,\end{aligned}$$

where w_i and ω_i denote the number and the share of stocks i, respectively, and ρ is the equi-correlation. In the following, we abstract from jumps in the variances and in the correlation. The proofs for the following equations are given in Appendix A, where we also consider the general case with jumps both in variances and in correlations.

For the dynamics of the derivative price $C_i = C_i(t, S_{i,t}, V_{i,t})$, it holds that

$$\begin{aligned}dC_{i,t} - r\,C_{i,t}dt &= \frac{\partial C_i}{\partial S_i}\left(dS_{i,t}^c - E_t^{\mathbb{Q}}[dS_{i,t}^c]\right) + \frac{\partial C_i}{\partial V_i}\left(dV_{i,t}^c - E_t^{\mathbb{Q}}[dV_{i,t}^c]\right)\\ &\quad + C_i(t, S_{i,t-}+\Delta S_{i,t}, V_{i,t-}) - C(t, S_{i,t-}, V_{i,t-})\\ &\quad - E_t^{\mathbb{Q}}[C_i(t, S_{i,t-}+\Delta S_{i,t}, V_{i,t-}) - C(t, S_{i,t-}, V_{i,t-})]\end{aligned}$$

where the superscript c denotes the continuous part of dS and dV. We approximate the jump component of dC by a second order Taylor-series. The excess return of C then becomes

$$\begin{aligned}dC_{i,t} - r\,C_{i,t}dt &= \frac{\partial C_i}{\partial S_i}\left(dS_{i,t} - r\,S_{i,t-}dt\right) + \frac{\partial C_i}{\partial V_i}\left(dV_{i,t} - E_t^{\mathbb{Q}}[dV_{i,t}]\right)\\ &\quad + \frac{1}{2}\frac{\partial^2 C_i}{\partial S_i^2}\left((\Delta S_{i,t})^2 - E^{\mathbb{Q}}[(\Delta S_{i,t})^2]\right) + \xi_{C_i,t} - E_t^{\mathbb{Q}}[\xi_{C_i,t}]\end{aligned} \tag{1}$$

where ξ is the remainder term from the Taylor series approximation. The expected excess return of C depends on the risk premiums for total stock price risk (multiplied by delta), for total variance risk (multiplied by vega), and risk premia on the higher order terms of the jump component. For the price of a derivative on the index we make the simplifying assumption that it depends on the level S_I and the variance V_I of the index only. The excess return of the derivative C_I then has the same form as the excess return of the derivatives C_i.

In general, C_I is exposed to changes in the underlying S_I and changes in the variance V_I. The exposure to changes in the variance can be decomposed into an exposure to the individual variances V_i, and changes in the correlation ρ of the diffusive stock price changes. In order to isolate the exposure to the correlation ρ, we follow Driessen et al. (2009) who rely on a so-called dispersion trade.[1] The idea is to take a long position in the index derivative and a short position in a basket of derivatives on the constituents in order to eliminate the exposures to individual variances and be left with an exposure to the correlation only. Furthermore, one has to eliminate the exposure to changes in the underlying index and the constituents. The derivatives that enter the dispersion trade should thus have zero delta and gamma. To construct these so-called variance-portfolios in a first step, we follow Cremers et al. (2015) and Middelhoff (2018).

In a similar way, the exposure of C_I to jumps in the underlying can be decomposed into an exposure to individual jumps and to co-jumps. Again, we use a dispersion trade to eliminate the exposure to individual jumps and to be left with an exposure to co-jumps only. Before we do so, however, we have to eliminate the exposure to diffusive stock price changes and to variance. The derivatives that enter the dispersion trade should now have zero delta and vega, and we again follow Cremers et al. (2015) and Middelhoff (2018) to construct these jump-portfolios.

[1] Note that Driessen et al. (2009) rely on a diffusion setup and thus assume that there are no stock price jumps.

Variance portfolio For the variance portfolio VOL, we consider individual derivatives which are delta- and gamma-neutral:

$$\frac{\partial VOL_I}{\partial S_I} = \frac{\partial VOL_i}{\partial S_i} = 0 \qquad \text{and} \qquad \frac{\partial^2 VOL_I}{\partial S_I^2} = \frac{\partial VOL_i^2}{\partial S_i^2} = 0.$$

We assume that their exposures to variance risk differ from zero. Plugging into Equation (1) gives the dynamics of the variance portfolio for stock i:

$$dVOL_{i,t} \;=\; r\,VOL_{i,t}dt + \frac{\partial VOL_i}{\partial V_i}\left(dV_{i,t} - E_t^{\mathbb{Q}}[dV_{i,t}]\right) + \xi_{VOL_i,t} - E_t^{\mathbb{Q}}[\xi_{VOL_i,t}].$$

This portfolio allows to trade changes in the variance of the stock. Its exposure to changes in the diffusive variance of the stock is given by its vega, and its expected excess return is the premium paid for this exposure to variance risk.

The dynamics of the variance portfolio for the index are

$$dVOL_{I,t} \;=\; r\,VOL_{I,t}dt + \frac{\partial VOL_I}{\partial V_I}\left(dV_{I,t} - E_t^{\mathbb{Q}}[dV_{I,t}]\right) + \xi_{VOL_I,t} - E_t^{\mathbb{Q}}[\xi_{VOL_I,t}],$$

where the dynamics of the variance of the index are

$$dV_I \;=\; \sum_{i=1} \frac{\partial V_I}{\partial V_i} dV_i^c + \frac{\partial V_I}{\partial \rho} d\rho^c + \frac{1}{2}\sum_{i=1}\sum_{j=1}\frac{\partial^2 V_I}{\partial V_i \partial V_j} dV_i^c dV_j^c + \frac{1}{2}\frac{\partial^2 V_I}{\partial \rho^2}(d\rho^c)^2 + \sum_{i=1}\frac{\partial^2 V_I}{\partial V_i \partial \rho} dV_i^c d\rho^c.$$

The variance portfolio VOL_I is thus exposed to changes in the individual variances and changes in the correlation. To hedge the exposure of VOL_I against changes in the variances V_i of the stocks, we add a short position in the individual derivatives C_i, where the size of the position in derivative i is

$$\frac{\frac{\partial VOL_I}{\partial V_I}}{\frac{\partial VOL_i}{\partial V_i}} \frac{\partial V_I}{\partial V_i}.$$

To simplify the analysis, we assume that the vegas of all variance portfolios coincide:

$$\frac{\partial VOL_I}{\partial V_I} = \frac{\partial VOL_i}{\partial V_i} = \text{constant}$$

The size of the position in derivative i is then equal to $\frac{\partial V_I}{\partial V_i}$. The excess return of the resulting portfolio $CorrVOL$ is

$$dCorrVOL_t - r\,CorrVOL_t\,dt \;=\; \frac{\partial VOL_I}{\partial V_I}\frac{\partial V_I}{\partial \rho}\left(d\rho_t - E_t^{\mathbb{Q}}[d\rho_t]\right) + \xi_{\text{CorrVOL},t} - E_t^{\mathbb{Q}}[\xi_{\text{CorrVOL},t}].$$

The expected excess return depends on the premium paid for the exposure to the equi-correlation, multiplied by the vega of the variance portfolio for the index, and the exposure of the variance of the index to the equi-correlation.

Jump portfolio For the jump portfolio, we consider individual derivatives which are delta- and vega-neutral:

$$\frac{\partial JUMP_I}{\partial S_I} = \frac{\partial JUMP_i}{\partial S_i} = 0 \qquad \text{and} \qquad \frac{\partial JUMP_I}{\partial V_I} = \frac{\partial JUMP_i}{\partial V_i} = 0.$$

The dynamics of the resulting jump portfolio for stock i are

$$dJUMP_{i,t} \;=\; r\,JUMP_{i,t}dt + \frac{1}{2}\frac{\partial^2 JUMP_i}{\partial S_i^2}\left((\Delta S_{i,t})^2 - E_t^{\mathbb{Q}}[(\Delta S_{i,t})^2]\right) + \xi_{JUMP_i,t} - E_t^{\mathbb{Q}}[\xi_{JUMP_i,t}],$$

and the dynamics of the index jump portfolio are

$$dJUMP_{I,t} \;=\; r\,JUMP_{I,t}dt + \frac{1}{2}\frac{\partial^2 JUMP_I}{\partial S_I^2}\left((\Delta S_{I,t})^2 - E_t^{\mathbb{Q}}[(\Delta S_{I,t})^2]\right) + \xi_{JUMP_I,t} - E_t^{\mathbb{Q}}[\xi_{JUMP_I,t}].$$

The squared jump in the index is

$$(\Delta S_{I,t})^2 \;=\; \sum_{i=1}^{N} w_i^2(\Delta S_{i,t})^2 + \sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N} w_i w_j \Delta S_{i,t}\Delta S_{j,t}.$$

The jump portfolio $JUMP_I$ is thus exposed to squared jumps of the single stocks and co-jumps of the stocks. To partly hedge against the jumps in single stocks, we add a short position in the individual derivatives, where the size of the position in derivative i is

$$\frac{\frac{\partial^2 JUMP_I}{\partial S_I^2}}{\frac{\partial^2 JUMP_i}{\partial S_i^2}}\, w_i^2.$$

In the following, we furthermore assume that the gammas of the variance portfolio are equal to each other

$$\frac{\partial^2 JUMP_I}{\partial S_I^2} = \frac{\partial^2 JUMP_i}{\partial S_i^2} = \text{constant}.$$

The position in derivative i is then given by w_i^2. The excess return of the resulting jump portfolio $CorrJUMP$ is

$$\begin{aligned}
&dCorrJUMP_t - r\, CorrJUMP_t\, dt \\
= \;\; & \frac{1}{2}\frac{\partial^2 JUMP_I}{\partial S_I^2} \sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} w_i w_j \left(\Delta S_{i,t}\Delta S_{j,t} - E_t^{\mathbb{Q}}\left[\Delta S_{i,t}\Delta S_{j,t}\right]\right) + \xi_{\text{CorrJUMP},t} - E_t^{\mathbb{Q}}[\xi_{\text{CorrJUMP},t}].
\end{aligned}$$

The expected excess return depends on the premiums paid for the exposure to co-jumps, multiplied by gamma of the jump portfolio for the index.

3 Empirical Evidence

3.1 Methodology

Our goal is to break the correlation risk premium down into two components: a premium related to the correlation of continuous stock price movements (CRP_{VOL}) and a premium for bearing the risk of co-jumps (CRP_{JUMP}). We follow the methodology outlined in Section 2 to construct portfolios which are only exposed to changes in the correlation of diffusive stock price movements and to co-jumps, respectively.

We build on Cremers et al. (2015) to construct the VOL and $JUMP$ portfolios introduced in Section 2 for the index and all constituents. On each day and for each underlying, we group all available liquid options according to their remaining time to maturity. Within every maturity bucket, we select the call and put option with the same strike price that are the nearest to at-the-money. If this selection criterium results in more than two straddles with different time to maturity, we choose the two straddles with the shortest and longest time to maturity because this results in the maximum dispersion of options' sensitivities and makes the later numerical optimization easier.[2] In order to make the returns on the VOL and $JUMP$ portfolios comparable over time and to simplify the initiation of the dispersion trade, we restrict the VOL and $JUMP$ portfolios to have constant sensitivities vega and gamma, respectively (see Middelhoff (2018)). Furthermore, we aim for a balanced allocation of wealth across the four options in order to minimize the impact of any outliers and potential data noise, e.g. stemming from bid-ask spreads. Thus, the optimization problem for the VOL portfolios can be written as

$$\min_{\mathbf{w}} \left|\left| \frac{\mathbf{w} \circ \mathbf{O}}{abs(\mathbf{w}^\top)\mathbf{O}} \right|\right|_2 \tag{2}$$

$$\text{s.t. } \mathbf{w}^\top \left[\boldsymbol{\Delta}, \mathcal{V}, \boldsymbol{\Gamma}\right] = [0, 200, 0] \tag{3}$$

$$\mathbf{w} \circ [-1, -1, 1, 1]^\top \geq \mathbf{0}, \tag{4}$$

[2] As noted in Section 3.2, we limit our attention to options with 14 to 365 days to expiration.

where $\mathbf{w} = [w_{call,T_1}, w_{put,T_1}, w_{call,T_2}, w_{put,T_2}]^\top$ denotes a 4×1 vector stacking the positions in call and put options with different times to maturity $T_1 < T_2$. $\mathbf{O}$ is the corresponding 4×1 vector of option prices, $\boldsymbol{\Delta}$, $\mathcal{V}$, and $\boldsymbol{\Gamma}$ are the corresponding 4×1 vectors of the option sensitivities delta, vega, and gamma, respectively. Equation (2) minimizes the Euclidean norm of all option positions relative to total wealth invested, which is defined as the sum of the absolute number of option contracts multiplied by their respective prices.

The VOL portfolios are constructed to be delta- and gamma-neutral and to always have a vega of 200. They short the straddle with time to maturity T_1 and go long the straddle with time to maturity T_2, because vega increases with time to maturity.

Analogously, when setting up the $JUMP$ portfolios, we optimize Equation (2)

$$\text{s.t. } \mathbf{w}^\top [\boldsymbol{\Delta}, \mathcal{V}, \boldsymbol{\Gamma}] = [0, 0, 0.01] \tag{5}$$

$$\mathbf{w} \circ [1, 1, -1, -1]^\top \geq \mathbf{0}, \tag{6}$$

such that they are delta- and vega-neutral and always have a gamma of 0.01. We go long the straddle with time to maturity T_1 and short the straddle with time to maturity T_2, because gamma decreases with time to maturity. We hold the optimal positions for one trading day and calculate the excess returns from the recorded closing prices of the following day. If we cannot recover an option, we interpolate its implied volatility using the kernel smoothing technique of OptionMetrics.[3]

The resulting VOL and $JUMP$ portfolio for constituent i (denoted as VOL_i and $JUMP_i$) are only exposed to changes in the individual variance and to individual jumps, respectively. In contrast, the VOL_I of the index portfolio is exposed to the correlation associated with continuous stock price movements (CRP_{VOL}) and on all individual variances. Analogously, the index $JUMP_I$ portfolio is exposed to co-jumps (CRP_{JUMP}) and to individual jumps

[3]More precisely, we interpolate across log time to maturity, moneyness defined as stock price divided by strike price, and a call-put identifier. We follow OptionMetrics and set the bandwidth parameters to $h_1 = 0.05$, $h_2 = 0.005$, and $h_3 = 0.001$.

in the stocks. In order to isolate CRP_{VOL} and CRP_{JUMP}, we hedge against the individual risk factors by taking appropriate positions when setting up the dispersion trade similar to Driessen et al. (2009).

3.2 Data

The sample period is from January 1996 to December 2017. Our analysis focuses on the S&P 100 index and its constituents. Data on the composition of the S&P 100 index is taken from Compustat, the level of the S&P 100 index is provided by OptionMetrics. We obtain daily stock price data on all constituents from the Center for Research in Security Prices (CRSP) and compute market capitalizations in order to approximate constituents' relative weights in the index. Daily option prices are taken from OptionMetrics IvyDB US. We apply several filters in the fashion of Goyal and Saretto (2009). First, we exclude options with non-standard settlement, missing implied volatility, and zero open interest. Second, we only keep options whose bid quotes are positive and strictly smaller than their ask quotes. Third, we compute midprices as the average of bid and ask quotes and discard options whose midprices violate standard arbitrage bounds as in Cao and Han (2013). We use the zero-coupon interest rate curve provided by OptionMetrics and linearly interpolate across time to maturity if necessary. When setting up the VOL and $JUMP$ portfolios as described in Section 3.1, we limit our attention to options with 14 to 365 days to expiration.

Options on the S&P 100 index and its constituents are American-style. Their recorded prices hence include an early exercise premium that distorts option returns. Since the accurate measurement of option returns is central to our analysis, we strip off the early exercise feature as follows. Given the recorded implied volatilities, we reprice all American options in binomial trees of Cox et al. (1979)-type with 1,000 time steps. We explicitly account for expected dividends using data on the S&P 100 dividend yield from OptionMetrics and data on discrete dividends paid by the constituents from OptionMetrics and CRSP. We eliminate options whose recorded prices deviate by more than 1% from the prices implied by the binomial trees. For the remaining options, we compute European prices using the same binomial trees and calculate option sensitivities as Black-Scholes greeks. We exclude options whose

European prices are zero.

3.3 Results

Having described the construction of option portfolios that isolate volatility and jump risk premiums as well as the identification of the corresponding correlation risk premiums, we now present the empirical findings for the S&P 100 index and its constituents.

3.3.1 Volatility Risk Premium

The VOL portfolios are only exposed to changes in the variance of the diffusive movements of the underlying as shown in Section 2. In particular, they experience positive returns when the realized change in variance exceeds the risk-neutral expectation (under $\mathbb{Q}$).

Index VRP Table 1 reports summary statistics of the returns on the VOL_I portfolio of the S&P 100 index. It shows that investors pay a premium to insure against volatility risk in the index. The annualized average return of the VOL_I portfolio is -2.77% with a standard deviation of 23.61% (first column).

Figure 1 shows the time series of VOL_I returns. The daily returns generally fluctuate around zero but occasionally are of great magnitude, both positive and negative. Notably, the time series exhibits an almost zero autocorrelation of -0.01 (p-value=0.28), which stands in stark contrast to the volatility risk premium. The top three returns were earned on February 27, 2007 (plunge in Chinese stock market, drop in orders for durable goods in the U.S.), September 17, 2008 (global financial crisis, rescue of A.I.G.), and October 27, 1997 (economic crisis in Asia, sell-off in Hong Kong). Figure 2 complements the analysis and plots the quantiles of VOL_I returns against the standard normal distribution (upper left graph). We observe that the time-series distribution is not normal and exhibits fat tails on both sides.

Individual VRP Turning to the S&P 100 constituents, we find that the individual volatility risk premiums are cross-sectionally dispersed. To illustrate this, Figure 3 plots the histogram of the time-series average returns of VOL_i portfolios across all constituents for which we have data over a period of at least half a year. In contrast to the negative index VRP, the individual VRPs are on average positive with a mean of 3.47% per year. Only 94 out of 195 constituents show negative VRPs.

Table 1 reports time-series averages of the properties of the cross-sectional distribution of VOL_i returns across the S&P 100 constituents. On average, we are able to construct VOL portfolios for 95 constituents on each day (third column). Furthermore, we find that investors *command* a premium to insure against individual volatility risk. The annualized average return of the VOL_i portfolios amounts to 1.60%, compared to -2.77% for the index. Stated differently, an equal-weighted investment in the VOL portfolios of all constituents yields positive returns on average, while an investment in the VOL portfolio of the index yields negative returns over the same period. This points towards a negative CRP_{VOL}, i.e. to a correlation which is larger under the risk-neutral measure than under the historical measure.

The above-mentioned cross-sectional dispersion is considerable and manifests in an annualized standard deviation of 24.16%. More importantly, the cross-sectional distribution is on average positively skewed. Notably, the average median return is negative and amounts to -0.03% per day. To shed light on the evolution of the cross-sectional dispersion, Figure 1 plots the 5% and 95% percentiles of the cross-sectional distribution of VOL_i returns over time. The deviation between the two percentiles is surprisingly small on most days. On some days, the two percentiles are so close to each other that they no longer cover the VOL_I return of the index, which as a result lies above or below the interval. Once in a while, the deviation between the two percentiles widens considerably. These days, however, do not necessarily coincide with extreme VOL_I returns. Taken together, the previous findings suggest that the overall positive average return is driven by the right tail of the distribution. This presumption is confirmed by Figure 2 which plots the quantiles of the pooled sample (upper right graph). It documents fat tails that are even more pronounced than those of the index and particularly strong for positive returns.

3.3.2 Jump Risk Premium

The $JUMP$ portfolios only load on jump risk as shown in Section 2. They exhibit positive returns when the realized jump in the underlying's price exceeds the risk-neutral expectation (under $\mathbb{Q}$).

Index JRP Table 1 shows that investors pay a large premium to insure against jump risk in the S&P 100 index. The premium amounts to economically meaningful -32.79% per year and fluctuates substantially over time as indicated by the annualized standard deviation of 36.90% (second column). Figure 1 plots the time series of $JUMP_I$ returns. The time series shows frequent spikes which are positive in most cases. These extreme positive returns are most likely the result of realized jumps in the index and corroborate the view that the $JUMP$ portfolios are indeed exposed to jump risk. The top three returns were earned on February 27, 2007 (see above), August 8, 2011 (U.S. credit rating downgrade), and October 27, 1997 (see above). While two of these dates happen to coincide with the dates of the top three VOL_I returns, Spearman's rho over the entire sample period indicates that the rank correlation is actually significantly negative at -0.17 (p-value=0.00) as reported in Panel B of Table 3. In addition, Figure 2 shows that the time-series distribution of $JUMP_I$ returns is not normal but has fat tails on both sides (lower left graph). The right tail is particularly pronounced and reflected in a positive skewness of the distribution.

Individual JRP With regard to the individual jump risk premiums of the S&P 100 constituents, Figure 3 points out that the cross-sectional dispersion is large. Across all constituents with a minimum of half a year of data, the individual JRP is on average negative with a mean of -8.38% per year. In fact, 121 out of 195 constituents show negative JRPs. Table 1 reports time-series averages of the properties of the cross-sectional distribution of $JUMP_i$ returns across the S&P 100 constituents. In line with intuition, we find that investors *pay* a premium to insure against individual jump risk. The annualized average return of the $JUMP_i$ portfolios is -7.24% (fourth column), compared to -32.79% for the index. Put differently, an equal-weighted investment in the $JUMP$ portfolios of all constituents yields much smaller negative returns on average than an investment in the $JUMP$ portfolio of the index. This points towards a negative CRP_{JUMP}. Yet, the above-mentioned cross-sectional distribution is substantially dispersed with an annualized standard deviation of 47.79% and positively skewed. However, our finding of a negative average individual JRP is robust to outliers since the median return is also negative and amounts to -0.38% per day.

Figure 1 shows that the cross-sectional dispersion is not only large but also subject to substantial variation over time. The 5% and 95% percentiles are far apart most of the time, and the $JUMP_I$ return of the index typically lies inside the interval. The deviation between the two percentiles widens frequently. Most, but not all, of these days are accompanied by extreme $JUMP_I$ returns. Every now and then, individual jump risk premiums experience strong upward movements, while the index jump risk premium does not change materially. Figure 2 confirms that the pooled sample of $JUMP_i$ returns exhibits fat tails and shows that they are indeed particularly pronounced on the right side (lower right graph).

3.3.3 Correlation Risk Premium

The above discussion has highlighted that the basket of constituents behaves very differently from the index. While the volatility risk premium on the S&P 100 index is negative, the individual volatility risk premiums on the constituents are positive on average. Similarly, the jump risk premium on the S&P 100 index is very large and negative, whereas the individual jump risk premiums on the constituents are negative on average, but much smaller. These two findings provide first indirect and preliminary evidence for the existence of economically meaningful correlation risk premiums CRP_{VOL} and CRP_{JUMP}.

Volatility CRP Table 2 reports summary statistics for the returns of the dispersion trade that is exposed to the correlation of diffusive changes in the stock price and thus collects CRP_{VOL}. Investors pay a premium of 10.16% per year to insure against states with a high correlation of the diffusive stock price components in which everyday changes of the stocks tend to have the same direction. This premium is economically meaningful and statistically significant at the 5% level (p-value=0.03). Note, however, that the returns of the VOL portfolios are scaled by their vega as shown in Section 2, so that the absolute level of the excess returns does not necessarily coincide with the correlation risk premium in index options. We thus also give the Sharpe ratio which is independent of the scaling of the portfolios. With an annualized standard deviation of CRP_{VOL} equal to 22.43%, selling insurance against states of high diffusive correlation yields a Sharpe ratio of 0.45 per year, which is in the ballpark of the Sharpe ratio of the S&P 100 index itself.

The second panel of Figure 4 shows the time series of CRP_{VOL} returns. Overall, the returns are often close to zero, negative on 53% of all days within the sample period, and subject to relatively large positive and negative spikes from time to time. Interestingly, periods of more volatile returns of CRP_{VOL} seem only loosely connected to returns of the S&P 100 index. For example, during the burst of the dot-com bubble in 2000 and the global financial crisis in 2008, index returns were the most extreme and volatile, whereas the returns of the CRP_{VOL} portfolio were surprisingly stable and close to zero with almost no swings at all. This suggests that there where no large sudden changes in the correlation or the correlation risk premium for diffusive stock price movements during these prominent crash periods.

The upper graph of Figure 5 gives the histogram for the returns of CRP_{VOL} over the sample period. The time-series distribution of CRP_{VOL} returns is symmetrically centered around zero and close to normally distributed. However, as previously discussed, it exhibits a few extreme returns on both sides of the distribution.

Figure 6 plots the time series of the long and short leg of the dispersion trade separately and hence allows insights into the sources of the profitability of trading insurance against states of high diffusive correlation. First of all, we observe that both legs offer returns that are of similar magnitude. Yet, the long leg, i.e. the position in the VOL portfolio of the S&P 100 index, varies more than the position in the basket of VOL portfolios of the constituents. This suggests that the return on the volatility portfolio of the index is mostly driven by the exposure to the correlation of continuous stock price movements, whereas the exposures to the individual variances are less relevant. This presumption is confirmed by the rank correlation of 0.85 (p-value=0.00) between CRP_{VOL} and VOL_I returns as reported in Panel B of Table 3.

The second panel of Figure 7 shows the cumulative log return of CRP_{VOL}. It is rather small and moves around zero in the first half of our sample until 2008, but then starts to steadily drop over time. The premium for the correlation between diffusive stock price changes is thus mainly earned (or paid) after 2008.

Jump CRP The premium associated with the risk of co-jumps amounts to -31.26% per year as shown in Table 2. In other words, investors are willing to pay an economically large premium to eliminate their exposure to correlated jumps among S&P 100 constituents. The premium has an annualized standard deviation of 36.89% and is statistically significant at the 1% level (p-value=0.00). Hence, selling insurance against states of high jump correlation provides a Sharpe ratio of 0.85. Compared to the premium for the correlation of continuous stock price movements, the premium for the correlation of jumps is much larger both in terms of average return and Sharpe ratio. Note, however, that the returns from the CRP_{JUMP} portfolio have a high kurtosis and that the Sharpe ratio does not take the risk of sudden large payoffs into account.

The lower panel of Figure 4 gives the time series of returns on CRP_{JUMP}. An investor who is long the correlation risk from sudden stock price changes occasionally earns very high positive returns (and an investor offering this insurance suffer from large losses). These extreme CRP_{JUMP} returns regularly coincide with extreme index returns. During calm periods when index returns are low and experience little volatility, e.g. between 2004 and 2007, we find stable CRP_{JUMP} returns. In contrast, during the burst of the dot-com bubble and the global financial crisis when index returns were the most extreme, CRP_{JUMP} returns spiked more frequently. This suggests that the risk premium stemming from the correlation of jumps is indeed related to stocks' sudden comovements and investors' increasing fear of co-jumps during crash periods.

In contrast, there is no obvious relation to extreme CRP_{VOL} returns. In fact, the rank correlation between the two correlation risk premiums over the entire sample period is negative at -0.25 (p-value=0.00) as reported in Panel B of Table 3.

Figure 5 displays the time-series distribution of CRP_{JUMP} returns and confirms that they are centered below zero and not normally distributed due to their extreme returns and positive skewness. Despite the rare extremely positive returns, CRP_{JUMP} returns are negative on 62% of all days within the sample period. Looking at the long and short leg of the dispersion trade separately, Figure 6 shows that the CRP_{JUMP} returns are overall very similar to the returns of the long leg. In contrast, returns of the short leg are much smaller in magnitude and show less frequent spikes. This result is not driven by the individual JRPs themselves which were found to be substantial in Section 3.3.2. It is rather the result of individual JRPs that cancel each other out due to diversification as well as the weighting of the short leg when initiating the dispersion trade. Individual JRPs are weighted by constituents' squared relative weights in the index. Hence, the average portfolio weight exponentially decays with the size of the index, which is almost 100 in our case. In other words, the larger the index, the smaller the probability that the index is significantly affected by jumps in a single constituent. Our results are therefore economically plausible and document that market jumps are almost exclusively driven by co-jumps among S&P 100 constituents.

The lower panel of Figure 7 shows the cumulative log return of CRP_{JUMP}. It steadily falls over the whole sample. The negative premium on co-jumps in the stocks is thus not characteristic of one particular time period, but exists over the whole sample period starting in 1996.

4 Conclusion

This paper analyzes the drivers of the correlation risk premium. More precisely, it breaks the correlation risk premium down into two components: a premium related to the correlation of continuous stock price movements and a premium for bearing the risk of co-jumps.

In order to empirically identify the risk premia, we construct option portfolios for the index as well as for its constituents. These portfolios directly load on changes in the volatility risk premium and in the jump risk premium, respectively. We find an economically and statistically significant volatility risk premium and jump risk premium for the S&P 100 index. Investors on average pay 2.77% per year in order to hedge market volatility risk and 32.79% to hedge against market jump risk. In contrast, these premia are much closer to zero for the constituents. Investors on average pay 7.24% per year to hedge against jumps in the constituents. In addition, investors even demand 1.60% per year to hedge out volatility risk of the constituents. The large differences in index and constituents risk premia are driven by significant correlation risk premia for both diffusive movements and co-jumps.

By setting up dispersion trades, we identify the correlation risk premium of diffusive movements and co-jumps, separately. While investors are on average willing to pay a premium to hedge both risks, the annualized premium paid to hedge co-jumps is much higher in magnitude (31.26% as opposed to 10.16%). Volatile and extreme market returns primarily go along with changes in the jump correlation risk premium and do not align with the volatility correlation risk premium. In addition, the variations of market volatility and market jump risk premia are almost exclusively explained by the corresponding correlation risk premia, with a correlation of 0.8508 for volatility and 0.9996 for jumps. Overall our results document the importance of correlation as a priced risk factor and highlight that the risk associated with co-jumps is of much greater importance than the correlation risk in diffusive price movements.

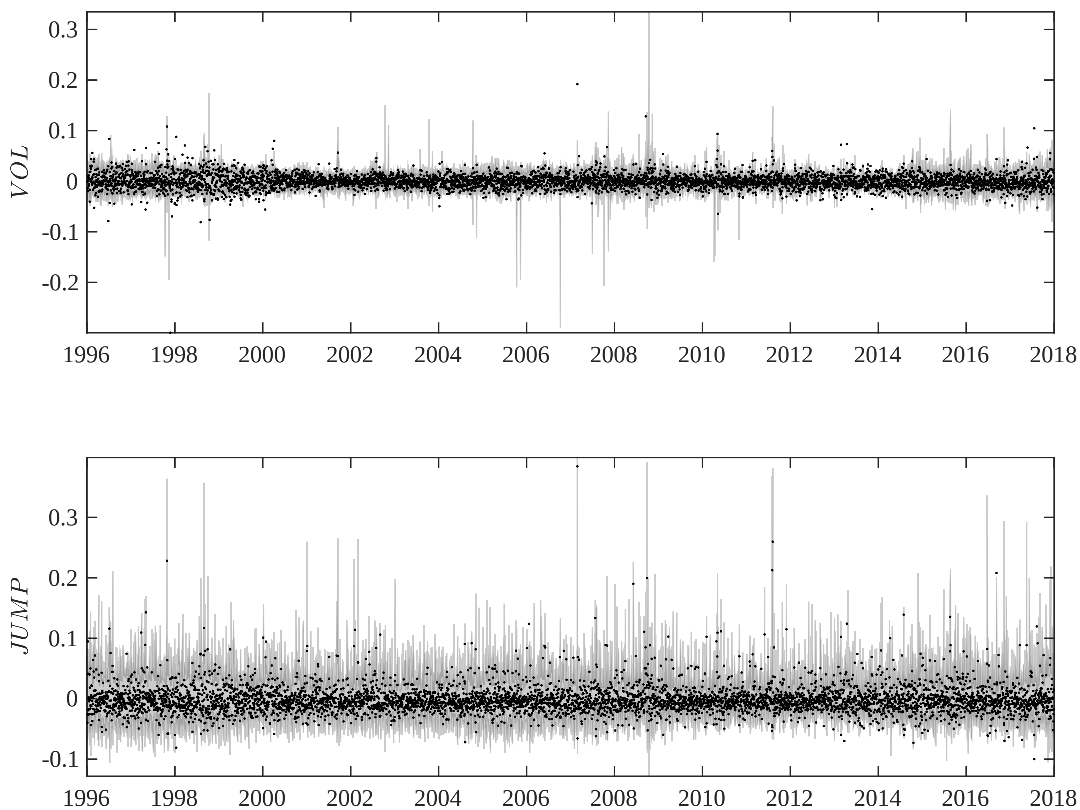

Figure 1: VOL and $JUMP$: Index and Cross-Sectional Distribution

This figure shows the time series of daily returns on the VOL and $JUMP$ portfolios of the S&P 100 index (from top to bottom). Data is taken from OptionMetrics within the sample period from January 1996 to December 2017. Shaded areas represent the distance between the 5% and 95% percentiles of the cross-sectional distribution of VOL and $JUMP$ returns across all constituents of the S&P 100 index.

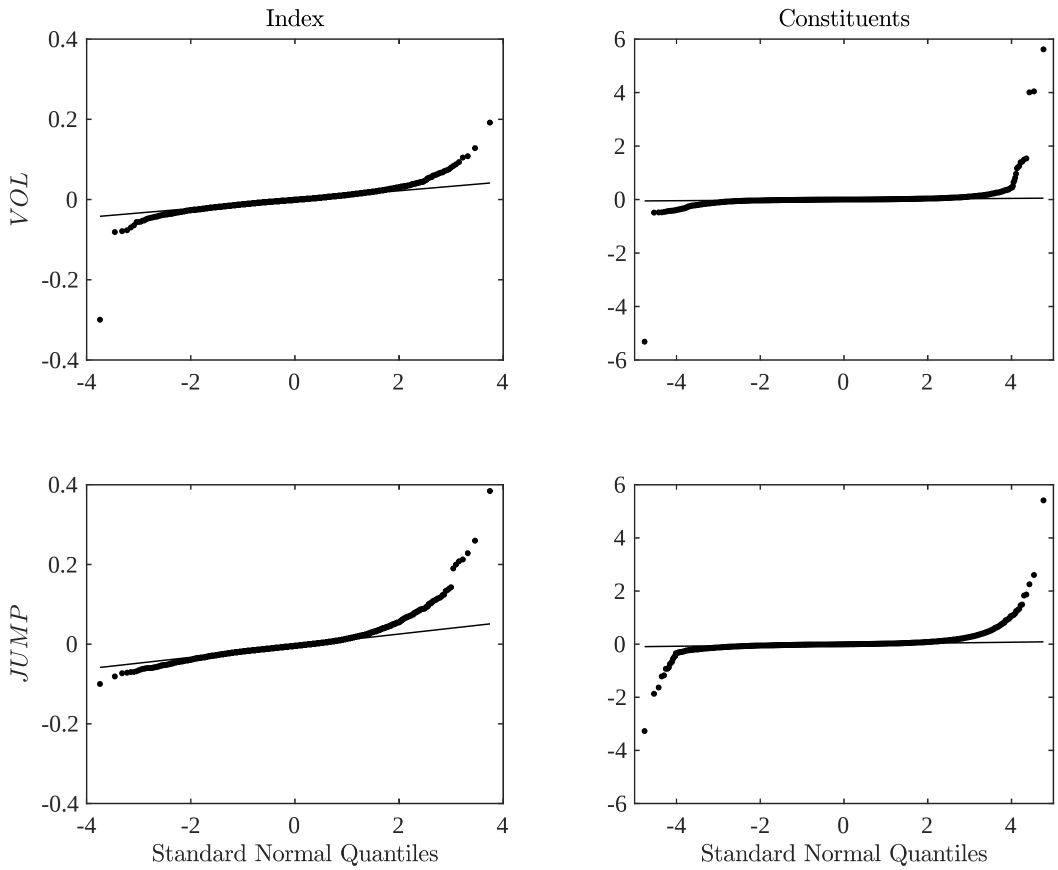

Figure 2: Quantile-Quantile Plots

This figure plots the quantile values of VOL and $JUMP$ returns (from top to bottom) on the S&P 100 index and its constituents (from left to right) against standard normal quantiles. Plots for the index are based on the time series of returns within the sample period from January 1996 to December 2017, while plots for the constituents are based on the pooled sample across stocks and time. Solid lines represent theoretical quantile values of fitted normal distributions.

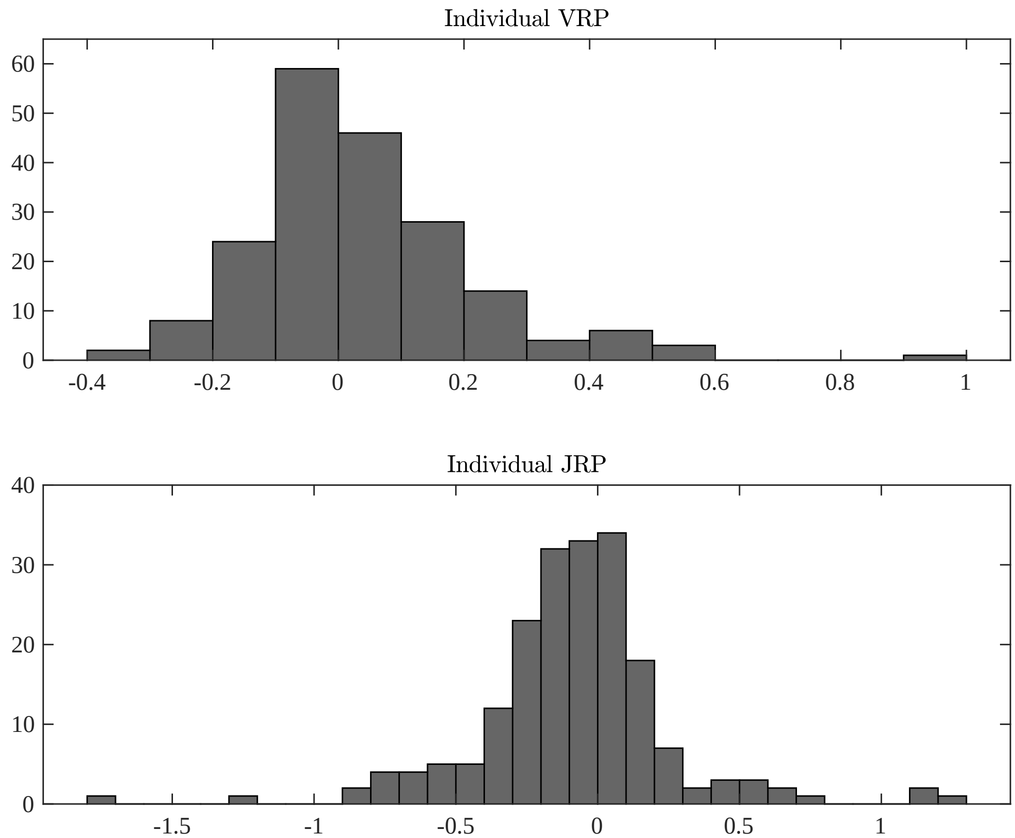

Figure 3: Cross-Sectional Distributions of Individual Risk Premiums

This figure shows the cross-sectional distributions of individual volatility and jump risk premiums (from top to bottom) across the constituents of the S&P 100 index. Individual volatility risk premiums (VRP) are defined as the annualized time-series averages of the VOL returns on each constituent. Analogously, individual jump risk premiums (JRP) are defined as the annualized time-series averages of $JUMP$ returns. The sample is restricted to constituents for which data is available over a period of at least half a year.

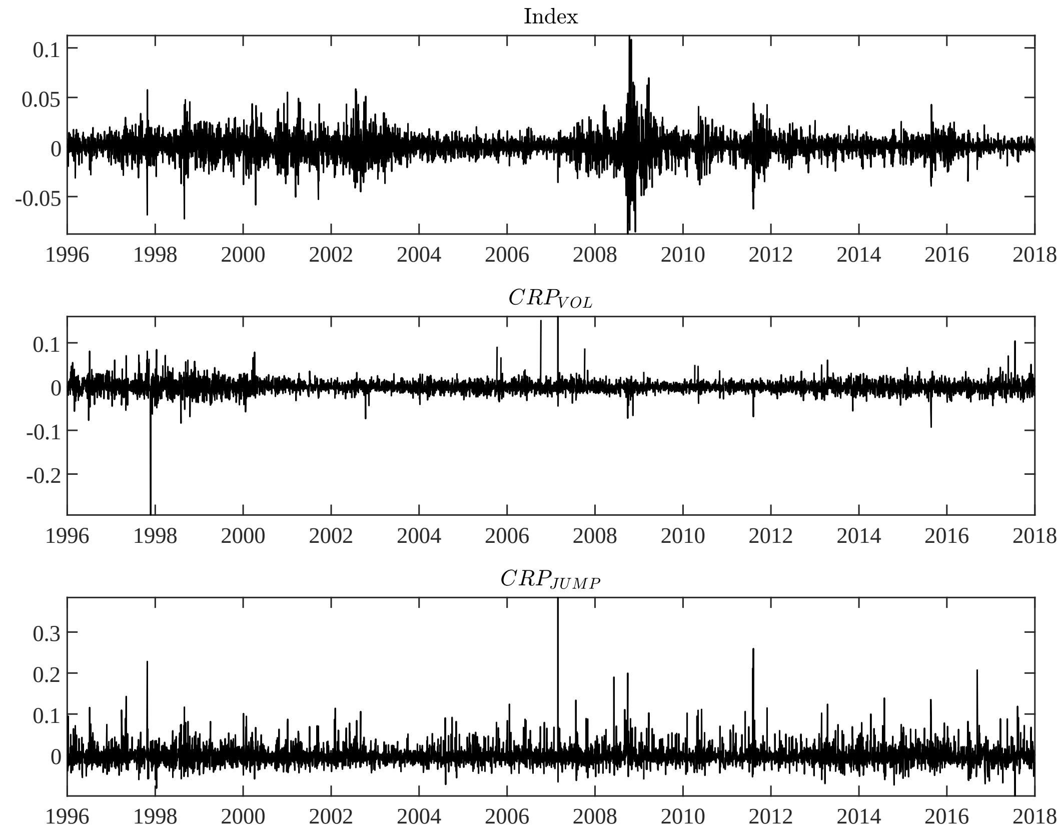

Figure 4: Index Returns and Correlation Risk Premiums

This figure shows the time series of daily returns on the S&P 100 index, the correlation risk premium for continuous stock price movements (CRP_{VOL}), and the correlation risk premium for co-jumps (CRP_{JUMP}) (from top to bottom). CRP_{VOL} and CRP_{JUMP} are based on dispersion trades that go long the VOL and $JUMP$ portfolios of the S&P 100 index, respectively, and short a basket of the corresponding portfolios of the constituents. The sample period is from January 1996 to December 2017.

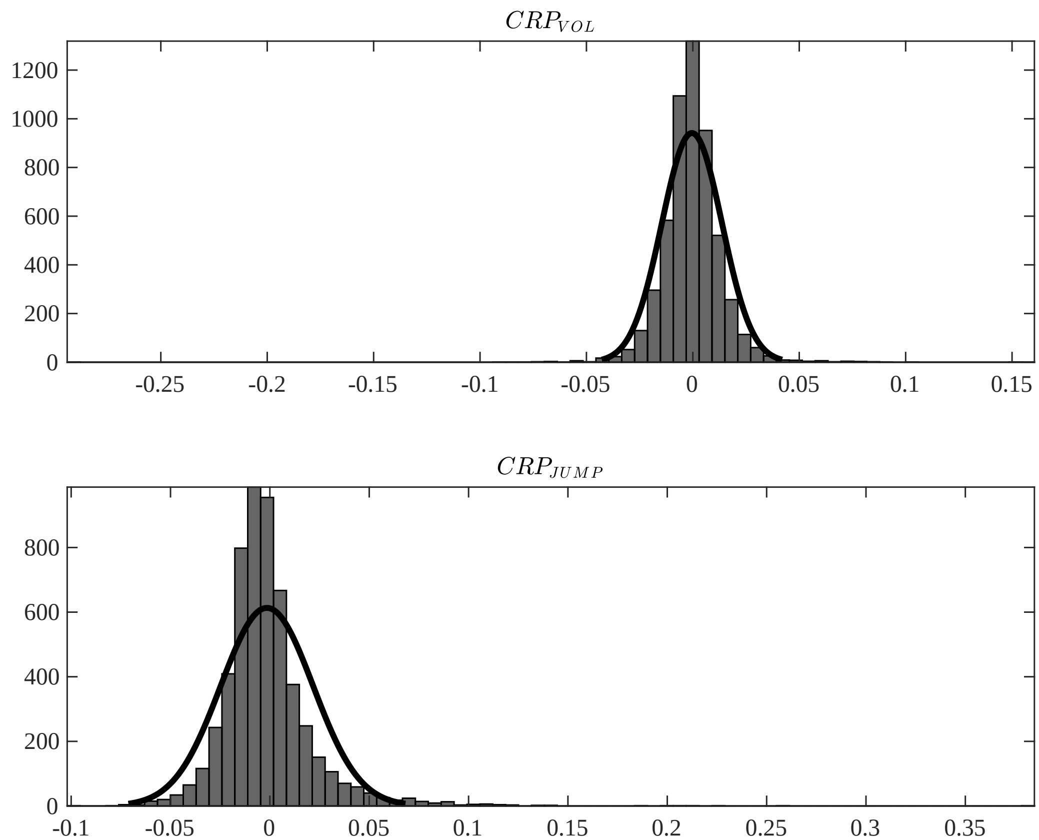

Figure 5: Time-Series Distributions of Correlation Risk Premiums

This figure shows the time-series distributions of correlation risk premiums (CRP) over the sample period from January 1996 to December 2017. CRP_{VOL} and CRP_{JUMP} are based on dispersion trades that go long the VOL and $JUMP$ portfolios of the S&P 100 index, respectively, and short a basket of the corresponding portfolios of the constituents. Solid lines represent fitted normal distributions.

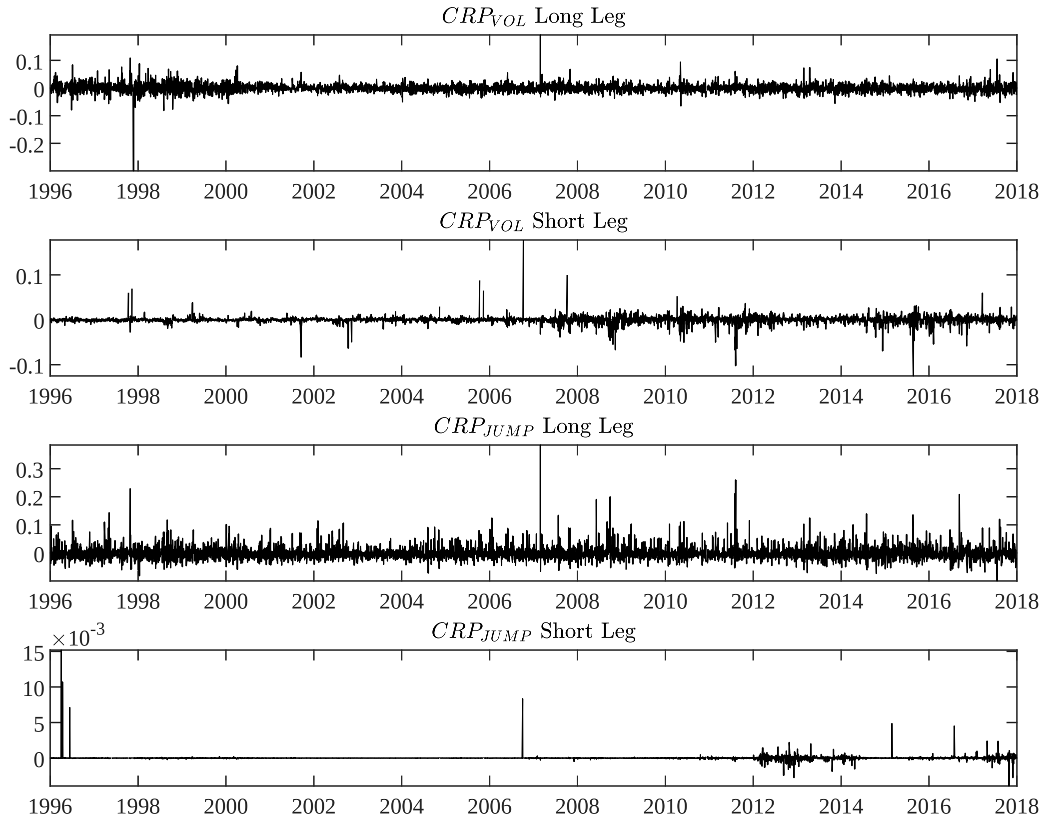

Figure 6: Dispersion Trade Components

This figure shows the time series of the long and short components of the dispersion trades for CRP_{VOL} and CRP_{JUMP}. The long leg represents a position in the VOL and $JUMP$ portfolios of the S&P 100 index, respectively, whereas the short leg represents a basket of positions in the corresponding portfolios of the constituents. The sample period is from January 1996 to December 2017.

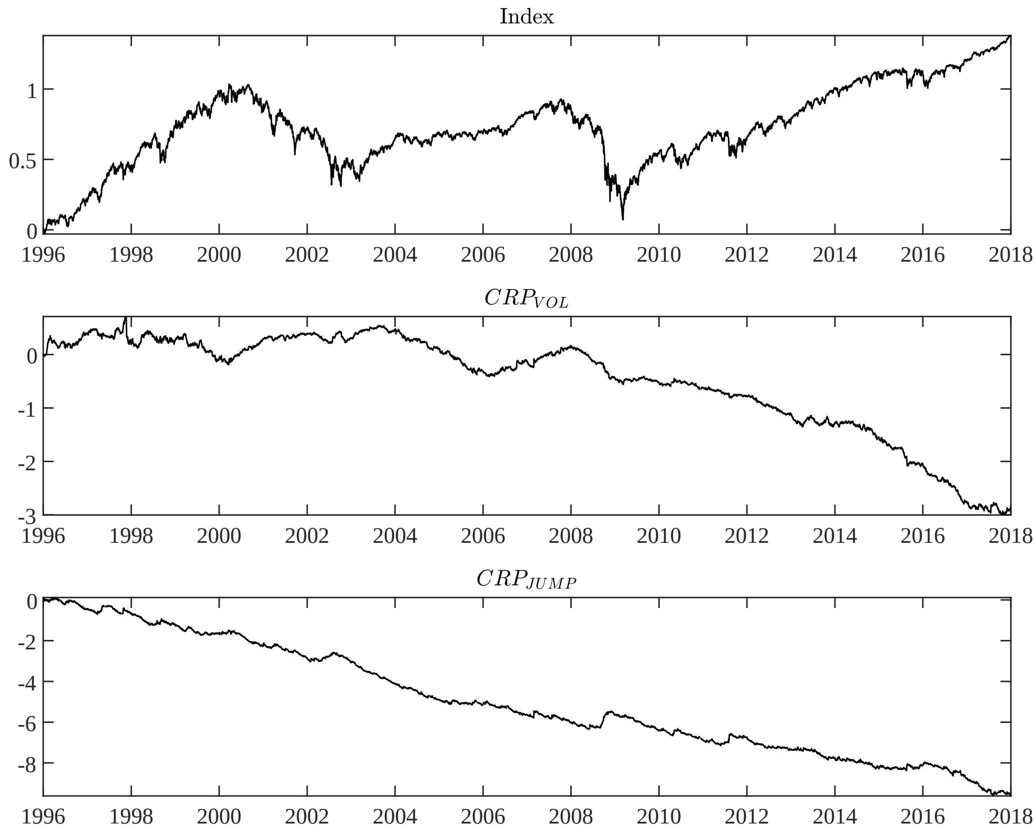

Figure 7: Cumulative Log Returns

This figure shows the cumulative log returns on the S&P 100 index, the correlation risk premium for continuous stock price movements (CRP_{VOL}), and the correlation risk premium for co-jumps (CRP_{JUMP}) (from top to bottom). CRP_{VOL} and CRP_{JUMP} are based on dispersion trades that go long the VOL and $JUMP$ portfolios of the S&P 100 index, respectively, and short a basket of the corresponding portfolios of the constituents. The sample period is from January 1996 to December 2017.

	Index		Constituents	
	VOL_I	$JUMP_I$	VOL_i	$JUMP_i$
Observations	5531	5531	95	95
Mean	-0.0277	-0.3279	0.0160	-0.0724
Standard Deviation	0.2361	0.3690	0.2416	0.4779
Median	-0.0007	-0.0044	-0.0003	-0.0038
Skewness	-0.4646	2.8413	0.3465	1.3773
Kurtosis	41.7802	28.8828	10.2940	12.1940

Table 1: VOL and $JUMP$: Summary Statistics

This table reports summary statistics of daily returns on the VOL and $JUMP$ portfolios of the S&P 100 index and its constituents (from left to right). Data is taken from OptionMetrics. Statistics for the index refer to the properties of the time-series distribution of returns over the sample period from January 1996 to December 2017, while statistics for the constituents refer to time-series averages of the properties of the cross-sectional distribution. Mean and standard deviation are reported at an annual level.

	CRP_{VOL}	CRP_{JUMP}
Mean	-0.1016	-0.3126
Standard Deviation	0.2243	0.3689
Sharpe Ratio	-0.4529	-0.8476
Median	-0.0007	-0.0043
Skewness	-0.8197	2.8492
Kurtosis	46.0288	28.9624

Table 2: CRP_{VOL} and CRP_{JUMP}: Summary Statistics

This table reports summary statistics of the correlation risk premium for continuous stock price movements (CRP_{VOL}) and the correlation risk premium for co-jumps (CRP_{JUMP}) (from left to right). CRP_{VOL} and CRP_{JUMP} are based on dispersion trades that go long the VOL and $JUMP$ portfolios of the S&P 100 index, respectively, and short a basket of the corresponding portfolios of the constituents. The sample period is from January 1996 to December 2017. Mean, standard deviation, and the Sharpe ratio are reported at an annual level.

Panel A: Pearson				
	VOL_I	$JUMP_I$	CRP_{VOL}	CRP_{JUMP}
VOL_I	1			
$JUMP_I$	0.0029	1		
CRP_{VOL}	0.8419	−0.1485	1	
CRP_{JUMP}	0.0035	0.9999	−0.1492	1
Panel B: Spearman				
VOL_I	1			
$JUMP_I$	−0.1666	1		
CRP_{VOL}	0.8508	−0.2449	1	
CRP_{JUMP}	−0.1650	0.9996	−0.2460	1

Table 3: Correlation Coefficients

This table reports pairwise correlation coefficients of daily returns on the VOL and $JUMP$ portfolios of the S&P 100 index (VOL_I and $JUMP_I$), the correlation risk premium for continuous stock price movements (CRP_{VOL}), and the correlation risk premium for co-jumps (CRP_{JUMP}). CRP_{VOL} and CRP_{JUMP} are based on dispersion trades that go long the VOL and $JUMP$ portfolios of the S&P 100 index, respectively, and short a basket of the corresponding portfolios of the constituents. The sample period is from January 1996 to December 2017. Panel A reports Pearson correlation coefficients and Panel B Spearman's rank correlation coefficients.

Appendix A Appendix

The dynamics of stock i are given by

$$\begin{aligned}
\frac{dS_{i,t}}{S_{i,t-}} &= \mu_i dt + \sqrt{V_{i,t}} dW_t^{Si} + \frac{\Delta S_{i,t}}{S_{i,t-}} \\
dV_{i,t} &= \mu_{Vi} dt + \sigma_{Vi} \sqrt{V_{i,t}} dW_t^{Vi} + \Delta V_{i,t}.
\end{aligned}$$

The index and its local variance are equal to

$$\begin{aligned}
S_{I,t} &= \sum_{i=1}^{N} w_i S_{i,t} \\
V_{I,t} &= \sum_{i=1}^{N} w_i^2 V_{i,t} + \sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} w_i w_j \sqrt{V_{i,t} V_{j,t}} \rho_t,
\end{aligned}$$

where ρ is the equi-correlation.

For the dynamics of the derivative price $C_i = C_i(t, S_{i,t}, V_{i,t})$, it holds that

$$\begin{aligned}
dC_{i,t} &= \frac{\partial C_i}{\partial t} dt + \frac{\partial C_i}{\partial S_i} dS_{i,t}^c + \frac{\partial C_i}{\partial V_i} dV_{i,t}^c + \frac{1}{2} \frac{\partial^2 C_i}{\partial S_i^2} (dS_{i,t}^c)^2 + \frac{1}{2} \frac{\partial^2 C_i}{\partial V_i^2} (dV_{i,t}^c)^2 + \frac{\partial^2 C_i}{\partial S_i \partial V_i} dS_{i,t}^c dV_{i,t}^c \\
&\quad + C_i(t, S_{i,t-} + \Delta S_{i,t}, V_{i,t-} + \Delta V_{i,t}) - C(t, S_{i,t-}, V_{i,t-}).
\end{aligned}$$

where the superscript c denotes the continuous parts of the changes dS_i and dV_i. The fundamental partial differential equation for C is given by

$$\begin{aligned}
r\, C_{i,t} &= \frac{\partial C_i}{\partial t} dt + \frac{\partial C_i}{\partial S_i} E_t^{\mathbb{Q}}[dS_{i,t}^c] + \frac{\partial C_i}{\partial V_i} E_t^{\mathbb{Q}}[dV_{i,t}^c] + \frac{1}{2} \frac{\partial^2 C_i}{\partial S_i^2} E_t^{\mathbb{Q}}[(dS_{i,t}^c)^2] + \frac{1}{2} \frac{\partial^2 C_i}{\partial V_i^2} E_t^{\mathbb{Q}}[(dV_{i,t}^c)^2] \\
&\quad + \frac{\partial^2 C_i}{\partial S_i \partial V_i} E_t^{\mathbb{Q}}[dS_{i,t}^c dV_{i,t}^c] + E_t^{\mathbb{Q}}[C_i(t, S_{i,t-} + \Delta S_{i,t}, V_{i,t-} + \Delta V_{i,t}) - C(t, S_{i,t-}, V_{i,t-})].
\end{aligned}$$

Subtracting the two equations from each other gives

$$\begin{aligned}
dC_{i,t} - r\, C_{i,t} &= \frac{\partial C_i}{\partial S_i} \left(dS_{i,t} - E_t^{\mathbb{Q}}[dS_{i,t}^c] \right) + \frac{\partial C_i}{\partial V_i} \left(dV_{i,t} - E_t^{\mathbb{Q}}[dV_{i,t}^c] \right) \\
&\quad + C_i(t, S_{i,t-} + \Delta S_{i,t}, V_{i,t-} + \Delta V_{i,t}) - C(t, S_{i,t-}, V_{i,t-}) \\
&\quad - E_t^{\mathbb{Q}}[C_i(t, S_{i,t-} + \Delta S_{i,t}, V_{i,t-} + \Delta V_{i,t}) - C(t, S_{i,t-}, V_{i,t-})].
\end{aligned}$$

The expected excess return of C thus depends on the risk premia for diffusive stock price risk (scaled by delta), for diffusive variance risk (scaled by vega), and on the premium for jump risk in the stock and in its variance.

For the following calculations, we approximate the jump component by a second order Taylor-series. The return of C becomes

$$
\begin{aligned}
dC_{i,t} &= r\,C_{i,t}dt + \frac{\partial C_i}{\partial S_i}\,(dS_{i,t} - r\,S_{i,t-}) + \frac{\partial C_i}{\partial V_i}\left(dV_{i,t} - E_t^{\mathbb{Q}}[dV_{i,t}]\right) \\
&\quad + \frac{1}{2}\frac{\partial^2 C_i}{\partial S_i^2}\left((\Delta S_{i,t})^2 - E^{\mathbb{Q}}[(\Delta S_{i,t})^2]\right) + \frac{1}{2}\frac{\partial^2 C_i}{\partial V_i^2}\left((\Delta V_{i,t})^2 - E_t^{\mathbb{Q}}[(\Delta V_{i,t})^2]\right) \\
&\quad + \frac{\partial^2 C_i}{\partial S_i \partial V_i}\left(\Delta S_{i,t}\Delta V_{i,t} - E_t^{\mathbb{Q}}[\Delta S_{i,t}\Delta V_{i,t}]\right) + \xi_{C_i,t} - E_t^{\mathbb{Q}}[\xi_{C_i,t}].
\end{aligned}
$$

The expected excess return of C depends on the risk premia for total stock price risk (scaled by delta), for total variance risk (scaled by vega), and risk premia on the higher order terms of the jump component.

The price of a derivative on the index depends on all stock price levels and on all local variances. In the following, we make the simplifying assumption that it depends on the level S_I and the variance V_I of the index only. The SDE for the derivative C_I then has the same form as the SDE for the derivatives C_i, and the same holds true for its excess return.

Variance portfolio For the variance-portfolio VOL, we consider individual derivatives which are delta- and gamma-neutral:

$$
\frac{\partial VOL_I}{\partial S_I} = \frac{\partial VOL_i}{\partial S_i} = 0 \qquad \text{and} \qquad \frac{\partial^2 VOL_I}{\partial S_I^2} = \frac{\partial VOL_i^2}{\partial S_i^2} = 0.
$$

We assume that their exposures to variance risk differ from zero.

The dynamics of the variance portfolio for stock i are

$$
\begin{aligned}
dVOL_{i,t} &= r\,VOL_{i,t}dt + \frac{\partial VOL_i}{\partial V_i}\left(dV_{i,t} - E_t^{\mathbb{Q}}[dV_{i,t}]\right) + \frac{1}{2}\frac{\partial^2 VOL_i}{\partial V_i^2}\left((\Delta V_{i,t})^2 - E_t^{\mathbb{Q}}[(\Delta V_{i,t})^2]\right) \\
&\quad + \frac{\partial^2 VOL_i}{\partial S_i \partial V_i}\left(\Delta S_{i,t}\Delta V_{i,t} - E_t^{\mathbb{Q}}[\Delta S_{i,t}\Delta V_{i,t}]\right) + \xi_{VOL_i,t} - E_t^{\mathbb{Q}}[\xi_{VOL_i,t}].
\end{aligned}
$$

This portfolio allows to trade changes in the variance of the stock. Its exposure to changes in the diffusive variance of the stock is given by its vega. Without jumps, the additional terms vanish. Its expected excess return is then the premium paid for this exposure to variance risk.

The dynamics of the variance portfolio for the index are

$$\begin{aligned} dVOL_{I,t} &= r\,VOL_{I,t}dt + \frac{\partial VOL_I}{\partial V_I}\Big(dV_{I,t} - E_t^{\mathbb{Q}}[dV_{I,t}]\Big) + \frac{1}{2}\frac{\partial^2 VOL_I}{\partial V_I^2}\Big((\Delta V_{I,t})^2 - E_t^{\mathbb{Q}}[(\Delta V_{I,t})^2]\Big) \\ &\quad + \frac{\partial^2 VOL_I}{\partial S_I \partial V_I}\Big(\Delta S_{I,t}\Delta V_{I,t} - E_t^{\mathbb{Q}}[\Delta S_{I,t}\Delta V_{I,t}]\Big) + \xi_{VOL_I,t} - E_t^{\mathbb{Q}}[\xi_{VOL_I,t}]. \end{aligned}$$

The dynamics of the index variance are

$$\begin{aligned} dV_I &= \sum_{i=1}\frac{\partial V_I}{\partial V_i}dV_i^c + \frac{\partial V_I}{\partial \rho}d\rho^c + \frac{1}{2}\sum_{i=1}\sum_{j=1}\frac{\partial^2 V_I}{\partial V_i \partial V_j}dV_i^c dV_j^c + \frac{1}{2}\frac{\partial^2 V_I}{\partial \rho^2}(d\rho^c)^2 + \sum_{i=1}\frac{\partial^2 V_I}{\partial V_i \partial \rho}dV_i^c d\rho^c \\ &\quad + V_I(V_{1,t-} + \Delta V_{1,t}, \ldots, V_{N,t-} + \Delta V_{N,t}, \rho_{t-} + \Delta\rho_t) - V_I(V_{1,t-}, \ldots, V_{N,t-}, \rho_{t-}). \end{aligned}$$

Again, a Taylor-series expansion of the last term gives

$$dV_I = \sum_{i=1}^{N}\frac{\partial V_I}{\partial V_i}dV_i + \frac{\partial V_I}{\partial \rho}d\rho + \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{\partial^2 V_I}{\partial V_i \partial V_j}dV_i dV_j + \frac{1}{2}\frac{\partial^2 V_I}{\partial \rho^2}(d\rho)^2 + \sum_{i=1}^{N}\frac{\partial^2 V_I}{\partial V_i \partial \rho}dV_i d\rho + \xi_{V_I,t}.$$

To hedge the exposure of VOL_I against changes in the variances V_i of the stocks, we add a short position in the individual derivatives C_i, where the size of the position in derivative i is

$$\frac{\frac{\partial VOL_I}{\partial V_I}}{\frac{\partial VOL_i}{\partial V_i}}\frac{\partial V_I}{\partial V_i}.$$

The dynamics of the resulting portfolio $CorrVOL$ are

$$\begin{aligned} &dCorrVOL_t \\ &\quad= r\left(VOL_{I,t} - \sum_{i=1}^{N}\frac{\frac{\partial VOL_I}{\partial V_I}}{\frac{\partial VOL_i}{\partial V_i}}\frac{\partial V_I}{\partial V_i}VOL_{i,t}\right)dt \\ &\qquad + \frac{\partial VOL_I}{\partial V_I}\frac{\partial V_I}{\partial \rho}\Big(d\rho_t - E_t^{\mathbb{Q}}[d\rho_t]\Big) \\ &\qquad + \frac{1}{2}\frac{\partial VOLI}{\partial V_I}\frac{\partial^2 V_I}{\partial \rho^2}\Big((\Delta\rho_t)^2 - E_t^{\mathbb{Q}}[(\Delta\rho_t)^2]\Big) \\ &\qquad + \frac{1}{2}\frac{\partial VOL_I}{\partial V_I}\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{\partial^2 V_I}{\partial V_i \partial V_j}\Big(\Delta V_{i,t}\Delta V_{j,t} - E_t^{\mathbb{Q}}[\Delta V_{i,t}\Delta V_{j,t}]\Big) \\ &\qquad + \frac{\partial VOL_I}{\partial V_I}\sum_{i=1}^{N}\frac{\partial^2 V_I}{\partial V_i \partial \rho}\Big(\Delta V_{i,t}\Delta\rho_t - E_t^{\mathbb{Q}}[\Delta V_{i,t}\Delta\rho_t]\Big) \end{aligned}$$

$$+\frac{1}{2}\frac{\partial^2 C_I}{\partial V_I^2}\left[(\Delta V_{I,t})^2 - E_t^{\mathbb{Q}}[(\Delta V_{I,t})^2] - \sum_{i=1}^{N}\frac{\frac{\partial VOL_I}{\partial V_I}}{\frac{\partial VOL_i}{\partial V_i}}\frac{\frac{\partial^2 VOL_i}{\partial V_i^2}}{\frac{\partial^2 VOL_I}{\partial V_I^2}}\frac{\partial V_I}{\partial V_i}\left((\Delta V_{i,t})^2 - E_t^{\mathbb{Q}}[(\Delta V_{i,t})^2]\right)\right]$$
$$+\frac{\partial^2 VOL_I}{\partial S_I \partial V_I}\left(\Delta S_{I,t}\Delta V_{I,t} - E_t^{\mathbb{Q}}[\Delta S_{I,t}\Delta V_{I,t}] - \sum_{i=1}^{N}\frac{\frac{\partial VOL_I}{\partial V_I}}{\frac{\partial VOL_i}{\partial V_i}}\frac{\frac{\partial^2 VOL_i}{\partial S_i \partial V_i}}{\frac{\partial^2 VOL_I}{\partial S_I \partial V_I}}\frac{\partial V_I}{\partial V_i}\left(\Delta S_{i,t}\Delta V_{i,t} - E_t^{\mathbb{Q}}[\Delta S_{i,t}\Delta V_{i,t}]\right)\right)$$
$$+\xi_{\mathrm{VOL},t} - E_t^{\mathbb{Q}}[\xi_{\mathrm{VOL},t}].$$

In the following, we furthermore assume that the vegas of the index and stock variance portfolios coincide:

$$\frac{\partial VOL_I}{\partial V_I} = \frac{\partial VOL_i}{\partial V_i} = \text{constant}$$

The excess return of the portfolio $CorrVOL$ then simplifies to

$$\begin{aligned}
&dCorrVOL_t \\
&= r\left(VOL_{I,t} - \sum_{i=1}^{N}\frac{\partial V_I}{\partial V_i}VOL_{i,t}\right)dt \\
&\quad + \frac{\partial VOL_I}{\partial V_I}\frac{\partial V_I}{\partial \rho}\left(d\rho_t - E_t^{\mathbb{Q}}[d\rho_t]\right) \\
&\quad + \frac{1}{2}\frac{\partial VOL_I}{\partial V_I}\frac{\partial^2 V_I}{\partial \rho^2}\left((\Delta\rho_t)^2 - E_t^{\mathbb{Q}}[(\Delta\rho_t)^2]\right) \\
&\quad + \frac{1}{2}\frac{\partial VOL_I}{\partial V_I}\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}\frac{\partial^2 V_I}{\partial V_i \partial V_j}\left(\Delta V_{i,t}\Delta V_{j,t} - E_t^{\mathbb{Q}}[\Delta V_{i,t}\Delta V_{j,t}]\right) \\
&\quad + \frac{\partial VOL_I}{\partial V_I}\sum_{i=1}^{N}\frac{\partial^2 V_I}{\partial V_i \partial \rho}\left(\Delta V_{i,t}\Delta\rho_t - E_t^{\mathbb{Q}}[\Delta V_{i,t}\Delta\rho_t]\right) \\
&\quad + \frac{1}{2}\frac{\partial^2 VOL_I}{\partial V_I^2}\left[(\Delta V_{I,t})^2 - E^{\mathbb{Q}}[(\Delta V_{I,t})^2] - \sum_{i=1}^{N}\frac{\frac{\partial^2 VOL_i}{\partial V_i^2}}{\frac{\partial^2 VOL_I}{\partial V_I^2}}\frac{\partial V_I}{\partial V_i}\left((\Delta V_{i,t})^2 - E_t^{\mathbb{Q}}[(\Delta V_{i,t})^2]\right)\right] \\
&\quad + \frac{\partial^2 VOL_I}{\partial S_I \partial V_I}\left(\Delta S_{I,t}\Delta V_{I,t} - E_t^{\mathbb{Q}}[\Delta S_{I,t}\Delta V_{I,t}] - \sum_{i=1}^{N}\frac{\frac{\partial^2 C_i}{\partial S_i \partial V_i}}{\frac{\partial^2 VOL_I}{\partial S_I \partial V_I}}\frac{\partial V_I}{\partial V_i}\left(\Delta S_{i,t}\Delta V_{i,t} - E_t^{\mathbb{Q}}[\Delta S_{i,t}\Delta V_{i,t}]\right)\right) \\
&\quad + \xi_{\mathrm{variance},t} - E_t^{\mathbb{Q}}[\xi_{\mathrm{variance},t}].
\end{aligned}$$

If there are no jumps in variances and in the correlation, the excess return of this portfolio is driven by the changes in the equi-correlation:

$$dCorrVOL_t - r\,CorrVOL_t dt = \frac{\partial VOL_I}{\partial V_I}\frac{\partial V_I}{\partial \rho}\left(d\rho_t - E_t^{\mathbb{Q}}[d\rho_t]\right) + \xi_{\mathrm{variance},t} - E_t^{\mathbb{Q}}[\xi_{\mathrm{variance},t}]$$

The expected excess return depends on the premium paid for the exposure to this equi-correlation, scaled by the vega and the exposure of the index' variance to the equi-correlation.

Jump portfolio For the jump-portfolio, we consider individual derivatives which are delta- and vega-neutral:

$$\frac{\partial JUMP_I}{\partial S_I} = \frac{\partial JUMP_i}{\partial S_i} = 0 \qquad \text{and} \qquad \frac{\partial JUMP_I}{\partial V_I} = \frac{\partial JUMP_i}{\partial V_i} = 0.$$

The dynamics of the resulting jump portfolio for stock i are

$$\begin{aligned} dJUMP_{i,t} &= r\, JUMP_{i,t}dt + \frac{1}{2}\frac{\partial^2 JUMP_i}{\partial S_i^2}\Big((\Delta S_{i,t})^2 - E_t^{\mathbb{Q}}[(\Delta S_{i,t})^2]\Big) \\ &+ \frac{1}{2}\frac{\partial^2 JUMP_i}{\partial V_i^2}\Big((\Delta V_{i,t})^2 - E_t^{\mathbb{Q}}[(\Delta V_{i,t})^2]\Big) \\ &+ \frac{\partial^2 JUMP_i}{\partial S_i \partial V_i}\Big(\Delta S_{i,t}\Delta V_{i,t} - E_t^{\mathbb{Q}}[\Delta S_{i,t}\Delta V_{i,t}]\Big) + \xi_{JUMP_i,t} - E_t^{\mathbb{Q}}[\xi_{JUMP_i,t}]. \end{aligned}$$

The dynamics of the index jump portfolio are

$$\begin{aligned} dJUMP_{I,t} &= r\, JUMP_{I,t}dt + \frac{1}{2}\frac{\partial^2 JUMP_I}{\partial S_I^2}\Big((\Delta S_{I,t})^2 - E_t^{\mathbb{Q}}[(\Delta S_{I,t})^2]\Big) \\ &+ \frac{1}{2}\frac{\partial^2 JUMP_I}{\partial V_I^2}\Big((\Delta V_{I,t})^2 - E_t^{\mathbb{Q}}[(\Delta V_{I,t})^2]\Big) \\ &+ \frac{\partial^2 JUMP_I}{\partial S_I \partial V_I}\Big(\Delta S_{I,t}\Delta V_{I,t} - E_t^{\mathbb{Q}}[\Delta S_{I,t}\Delta V_{I,t}]\Big) + \xi_{JUMP_I,t} - E_t^{\mathbb{Q}}[\xi_{JUMP_I,t}]. \end{aligned}$$

The squared jump in the index is

$$(\Delta S_{I,t})^2 = \sum_{i=1}^{N} w_i^2 (\Delta S_{i,t})^2 + \sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} w_i w_j \Delta S_{i,t}\Delta S_{j,t}.$$

To partly hedge against this jump, we add a short position in the individual derivatives, where the size of the position in derivative i is

$$\frac{\frac{\partial^2 JUMP_I}{\partial S_I^2}}{\frac{\partial^2 JUMP_i}{\partial S_i^2}} w_i^2.$$

The dynamics of the resulting jump portfolio $CorrJUMP$ are

$dCorrJUMP_t$

$$
\begin{aligned}
= \quad & r\left(JUMP_{I,t} - \sum_{i=1}^{N} \frac{\frac{\partial^2 JUMP_I}{\partial S_I^2}}{\frac{\partial^2 JUMP_i}{\partial S_i^2}} w_i^2 JUMP_{i,t}\right) dt \\
& + \frac{1}{2}\frac{\partial^2 JUMP_I}{\partial S_I^2} \sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} w_i w_j \left(\Delta S_{i,t}\Delta S_{j,t} - E_t^{\mathbb{Q}}\left[\Delta S_{i,t}\Delta S_{j,t}\right]\right) \\
& + \frac{1}{2}\frac{\partial^2 JUMP_I}{\partial V_I^2}\left((\Delta V_{I,t})^2 - E^{\mathbb{Q}}\left[(\Delta V_{I,t})^2\right] - \sum_{i=1}^{N} \frac{\frac{\partial^2 JUMP_I}{\partial S_I^2}}{\frac{\partial^2 JUMP_i}{\partial S_i^2}} \frac{\frac{\partial^2 JUMP_i}{\partial V_i^2}}{\frac{\partial^2 JUMP_I}{\partial V_I^2}} w_i^2 \left((\Delta V_{i,t})^2 - E_t^{\mathbb{Q}}[(\Delta V_{i,t})^2]\right)\right) \\
& + \frac{\partial^2 JUMP_I}{\partial S_I \partial V_I}\left(\Delta S_{I,t}\Delta V_{I,t} - E_t^{\mathbb{Q}}\left[\Delta S_{I,t}\Delta V_{I,t}\right] - \sum_{i=1}^{N} \frac{\frac{\partial^2 JUMP_I}{\partial S_I^2}}{\frac{\partial^2 JUMP_i}{\partial S_i^2}} \frac{\frac{\partial^2 JUMP_i}{\partial S_i \partial V_i}}{\frac{\partial^2 JUMP_I}{\partial S_I \partial V_I}} w_i^2 \left(\Delta S_{i,t}\Delta V_{i,t} - E_t^{\mathbb{Q}}\left[\Delta S_{i,t}\Delta V_{i,t}\right]\right)\right) \\
& + \xi_{\mathrm{JUMP},t} - E^{\mathbb{Q}}[\xi_{\mathrm{JUMP},t}].
\end{aligned}
$$

In the following, we furthermore assume that

$$
\frac{\partial^2 JUMP_I}{\partial S_I^2} = \frac{\partial^2 JUMP_i}{\partial S_i^2} = \text{constant}.
$$

The return of the portfolio $CorrJUMP$ then simplifies to

$$
\begin{aligned}
& dCorrJUMP_t \\
= \quad & r\, CorrJUMP_t dt + \frac{1}{2}\frac{\partial^2 JUMP_I}{\partial S_I^2} \sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} w_i w_j \left(\Delta S_{i,t}\Delta S_{j,t} - E^{\mathbb{Q}}\left[\Delta S_{i,t}\Delta S_{j,t}\right]\right) \\
& + \frac{1}{2}\frac{\partial^2 JUMP_I}{\partial V_I^2}\left((\Delta V_{I,t})^2 - E_t^{\mathbb{Q}}\left[(\Delta V_{I,t})^2\right] - \sum_{i=1}^{N} \frac{\frac{\partial^2 C_i}{\partial V_i^2}}{\frac{\partial^2 C_I}{\partial V_I^2}} w_i^2 \left[(\Delta V_{i,t})^2 - E^{\mathbb{Q}}[(\Delta V_{i,t})^2]\right]\right) \\
& + \frac{\partial^2 JUMP_I}{\partial S_I \partial V_I}\left(\Delta S_{I,t}\Delta V_{I,t} - E^{\mathbb{Q}}\left[\Delta S_{I,t}\Delta V_{I,t}\right] - \sum_{i=1}^{N} \frac{\frac{\partial^2 JUMP_i}{\partial S_i \partial V_i}}{\frac{\partial^2 JUMP_I}{\partial S_I \partial V_I}} w_i^2 \left(\Delta S_{i,t}\Delta V_{i,t} - E_t^{\mathbb{Q}}\left[\Delta S_{i,t}\Delta V_{i,t}\right]\right)\right) \\
& + \xi_{\mathrm{JUMP},t} - E_t^{\mathbb{Q}}[\xi_{\mathrm{JUMP},t}].
\end{aligned}
$$

If there are no jumps in variances and in the correlation, the excess return of this portfolio is driven by the joint jumps in stock prices:

$$
\begin{aligned}
& dCorrJUMP_t - r\, CorrJUMP_t\, dt \\
= \quad & \frac{1}{2}\frac{\partial^2 JUMP_I}{\partial S_I^2} \sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} w_i w_j \left(\Delta S_{i,t}\Delta S_{j,t} - E_t^{\mathbb{Q}}\left[\Delta S_{i,t}\Delta S_{j,t}\right]\right) + \xi_{\mathrm{JUMP},t} - E_t^{\mathbb{Q}}[\xi_{\mathrm{JUMP},t}].
\end{aligned}
$$

The expected excess return depends on the premium paid for the exposure to joint jumps, scaled by gamma.

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