The harvester's guide to the (volatility) galaxy

Primer

29 September 2017

Volatility is a unique asset; understanding its nature is key

Volatility is a unique and often misunderstood asset; it is very different in some ways from equities and bonds and in other ways similar. For instance, while traditional asset returns are generally uncorrelated with past returns, realised vol is strongly dependent on past vol. At the same time, vol changes are better represented as % returns (like in equities), which is at odds with the market norm of specifying vol risk in point changes.

What is Volatility Risk Premium (VRP) & why does it exist

Markets tend to overestimate future realised volatility in the long run – this creates a positive VRP. Measuring VRP using the popular implied-realised volatility spread underestimates losses (and gains) of short vol trades and is not directly tradable. We define VRP instead using the implied to realised variance spread (variance = vol^2). As to why it exists, option prices, like insurance premia, need to compensate sellers for the risk of rare but large payouts. Aside this, supply-demand imbalances in different option markets also play a big role in deciding the extent of the premium and how it evolves.

Short volatility vehicle, sizing & tenor choices are critical

Variance and volatility swaps offer the cleanest exposure to VRP, whereas delta-hedged option implementations are path-dependent, albeit offering exchanged-listed and even customisable exposure. Focussing on variance swaps, our hypothetical back-testing since 2001 suggests that a typically sized short S&P500 1m var strategy would have had 3x the Sharpe, 2x the Calmar ratio and a faster recovery time than being long the S&P500. Moreover, sizing short var strategies based on the (inverse) level of vol (ratio-sized) versus fixed (%) vega sizing further improved Sharpe ratios and reduced losses. Regarding tenors, we prefer shorter-dated tenors as greater VRP in longer tenors (due to steep vol term structures) is also associated with greater volatility of term premium.

VRP strategies enhance equity & x-asset factor portfolios

Partly replacing equities with short vol exposure has significant merit given short vol's high correlation to equities, superior risk-adjusted returns and faster recovery times. Our back-testing shows that since 2001, even a 5% short vol allocation would have improved equity Sharpe by 0.05 while limiting tracking error to 1% p.a. Also, building on our prior risk factor work, we find that a tail-aware equal risk contribution portfolio of x-asset risk factors (including short vol) would have improved portfolio Sharpe by 0.4 since 2009. Finally, we show how hedging the residual market beta of short vol strategies can create market-neutral VRP exposure, which is consistent with (long-short) risk factor portfolios.

VRP harvesting makes sense even when vol is low

Contrary to popular belief, history shows that the risk-reward of selling vol is better in low vol regimes. Moreover, short vol strategies typically have longer runs of consecutive gains in low vs high vol regimes. Finally, vol rarely jumps from low to sustained high vol regimes; there tends to be a progression that allows implied vol to reprice accordingly.

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Introduction

> "DON'T PANIC" (in large friendly letters)
>
> - from The Hitchhiker's Guide to the Galaxy (*and sound advice for volatility sellers*)

Volatility and uncertainty. Volatility is an asset that is often and easily misunderstood, in our view. A simple example that supports this is when some market commentators conflate uncertainty as related to low conviction with a need to see higher price volatility. However, this misses the point that if there is little conviction or consensus on market direction, buyers and sellers are more likely to be matched, resulting in greater price stability (low volatility). So in a sense, greater uncertainty or diverse views can lead to lower volatility. Similarly, when enough market participants are convinced that asset prices need to fall (or rise), then greater pressure from sellers (or buyers) can lead to large price movements (higher volatility).

Implied versus realised volatility. Of course, uncertainty about the trajectory of asset prices may well and in fact does manifest itself in the price of volatility going forward (implied), which is distinct from the volatility being experienced by markets (realised). Enter the volatility risk premium (VRP), which is often simply defined as the difference between these two quantities. Indeed, papers on harvesting VRP have become a bit of a cottage industry, particularly as there is generally less familiarity with volatility as an asset compared to other 'real' assets. This has necessitated an ongoing phase of education for market participants outside the niche 'volatility professionals' category.

However, there is a gap in this market that we believe needs to be addressed, which sits squarely between having *accessible* VRP research for market practitioners and having a practical, in-depth discussion about the how and why of trading volatility. Our goal in this piece is to attempt this tricky balance. To do so, we believe it is important to organise our content carefully and understand:

1. **The nature of realised volatility** (pg 3), how it is distributed and what this means for the risk of short volatility strategies.

2. **Why volatility risk premium (VRP) exists** (pg 9) in the first place, what drives it and what biases may be introduced if it is naively defined

3. **How we may extract VRP** (pg 13), with particular attention to implementation trade-offs, focussing on variance swaps, their sizing, tenor considerations and more

4. **How VRP strategies can fit into broad portfolios** (pg 23), whether it is in the context of equity replacement or indeed within a cross asset risk factor portfolio

5. **Why harvesting VRP makes more sense even in low volatility regimes** (pg 28), where risk/reward is *actually* skewed in favour of such strategies.

Importantly, we do not introduce any element of market timing in our analysis here. While there is clearly a space for significant alpha generation from successful market timing, the difficulties of being consistently right (and the costs of being wrong) are also well documented. For now, we focus on how to navigate the choices involved in and the portfolio implications of systematically harvesting volatility risk premium.

Volatility is unique; understanding it is key

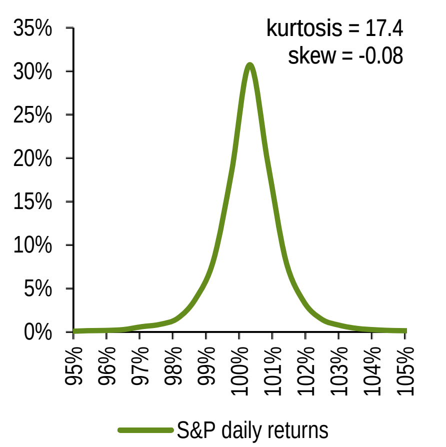
- The distribution of realised volatility (RV) is fat-tailed
- RV changes are negatively correlated to risk asset returns
- RV is auto-correlated, leading to clustering behaviour
- RV is mean-reverting but the speed of mean-reversion varies
- Subsequent RV point changes are positively correlated to volatility

Before we may confidently reason about volatility risk premium, it is important to study the nature of realised volatility, a statistical measure of the variability of asset returns. Given it is commonly associated with the notion of risk, realised volatility or variance (volatility squared) is not only critical for trading volatility, it plays a key role in portfolio risk management and asset allocation. In this section, we summarise some key observations about the distribution of realised volatility (and variance).

Realised volatility exhibits fat tails

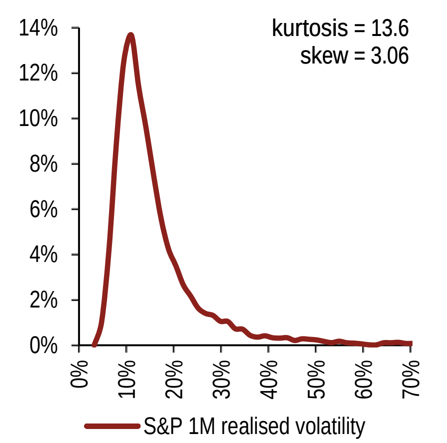
Chart 1 to Chart 3 show the distributions of S&P500 (S&P) daily returns, 1m realised volatility and 1m realised variance since 1927. The charts show that the distribution of realised variance is more asymmetric (has greater skewness) than that of realised volatility, which in turn is more skewed than the distribution of S&P returns. Furthermore, the distribution of realised variance is more peaked (4-5x higher kurtosis) than that of realised volatility and S&P returns. This is an important fact to remember for strategies that are short variance, as we shall show later.

Chart 1: S&P returns exhibit fat tails...



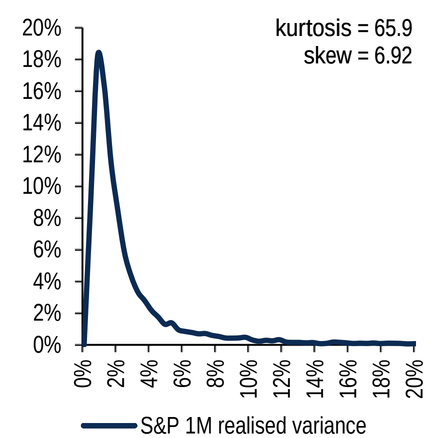
Source: BofA Merrill Lynch Global Research. Data: 10-Dec-1927 to 16-Aug-17.

Chart 2:...so RV is also fat-tailed & skewed...



Source: BofA Merrill Lynch Global Research. Data: 10-Dec-1927 to 16-Aug-17.

Chart 3: ... and realised var even more so

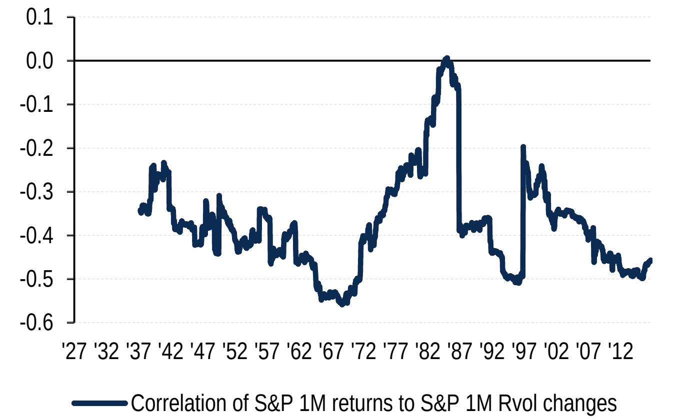


Source: BofA Merrill Lynch Global Research. Data: 10-Dec-1927 to 16-Aug-17.

Realised vol changes for risk assets are negatively correlated to asset returns

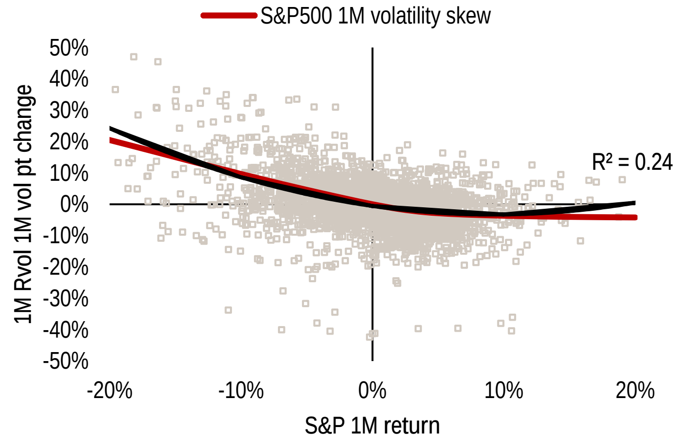
For equities and other risk assets, negative returns, particularly over shorter periods, tend to be more pronounced than positive ones as negative news tends to disrupt the status quo more meaningfully than positive surprises. Later in this piece we show that (rising) stock correlations in equity selloffs are an important driver of this behaviour for equity indices. Consequently, realised vol usually rises as risk assets decline. Chart 4 shows the relationship between asset returns and realised vol over time for the S&P. This observation of course also explains the existence of implied volatility skew, i.e., the fact that out-of-the-money put options are priced at a higher implied volatility to out-of-the-money call options (Chart 5).

Chart 4: S&P monthly returns have been consistently negatively correlated to realised volatility changes…



Source: BofA Merrill Lynch Global Research. Data: 10-Dec-1927 to 16-Aug-17.Rolling 10y correlation.

Chart 5: … which helps explain the existence of implied vol skew

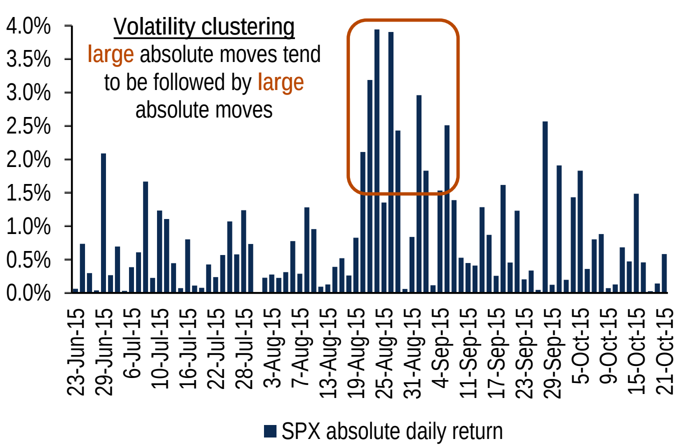


Source: BofA Merrill Lynch Global Research. Data: 3-Jan-10 to 5-Sep-17. Skew is an average of historical skew levels since May-09.

While returns are uncorrelated, absolute returns exhibit strong auto-correlation

While asset price changes are random and typically unpredictable[1], large price changes are much more likely to be followed by more large changes, and small changes are more likely to be followed by small changes – a property commonly called volatility clustering[2] (Chart 6). In other words, while returns are un-correlated, volatility (i.e. absolute returns) exhibits strong auto-correlation (Chart 8 and Chart 9). This persistence of volatility in benign market conditions or in market shocks is more pronounced during bear markets than during rallies (Chart 7). A potential rationalisation of this observation is that an initial sell-off may be followed by either further contagion or a swift containment, both of which can result in subsequent large moves over the following periods. Importantly, clustering has been a persistent phenomenon over time (see Appendix, Chart 67).

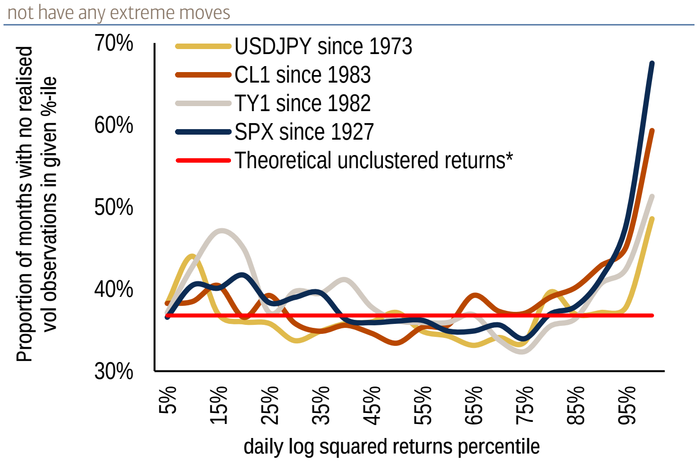
Chart 6: Rare events (disproportionately large absolute returns) tend to be 'clustered' together in a short time period



Source: BofA Merrill Lynch Global Research. Data: 23-Jun-15 to 21-Oct-15.

Chart 7: Across asset classes, clustering of absolute returns has been more evident for large moves than for small moves

95th percentile absolute moves were disproportionally 'clustered' as most months did not have any extreme moves

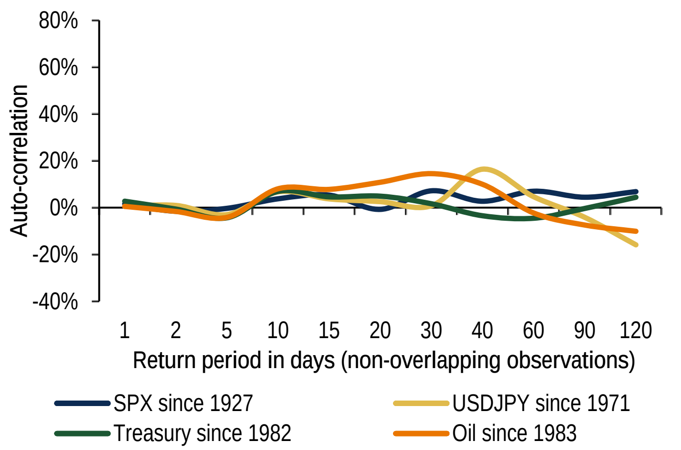


Source: BofA Merrill Lynch Global Research. Data: Dec-1927 to Apr-17. *Assuming daily returns are independently and identically distributed, it can be shown that the expected number of months which contain no observation belonging to a given set of observations of size P (e.g., the 0th to 5th percentile bucket) is given by (1-1/M)^P, where M is the total number of months. If P is roughly equal to M (as is the case here since 21 days x M = total number of observations = 20 x P) and M is large enough, this can be approximated by exp(-1), which is the red line in the chart.

[1] There is arguably some degree of mean reversion in extreme market moves (Poterba, Summers, Mean Reversion in Stock Prices: Evidence and Implications, National Bureau of Economic Research, 1987)

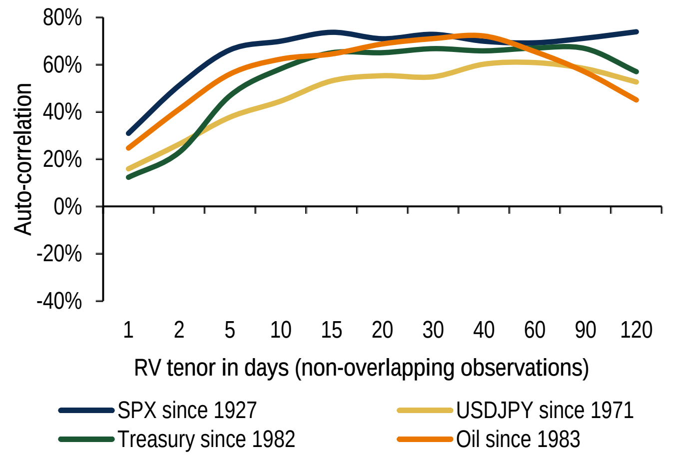
[2] Mandelbrot, B. B., The Variation of Certain Speculative Prices, The Journal of Business 36, No. 4, 1963

Chart 8:Returns over various time-frames are generally uncorrelated in the case of equities, FX, commodities and rates...



Source: BofA Merrill Lynch Global Research. Data: Dec-1927 to Apr-17.

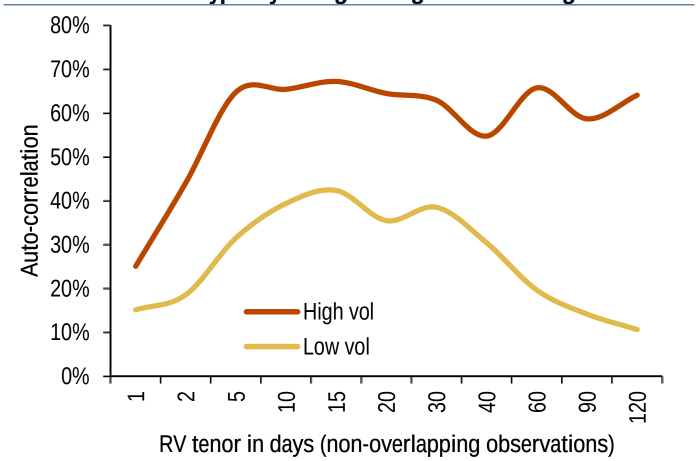
Chart 9: ...but future realised volatility is strongly related to the current level of realised volatility, i.e., it exhibits auto-correlation



Source: BofA Merrill Lynch Global Research. Data: Dec-1927 to Apr-17.

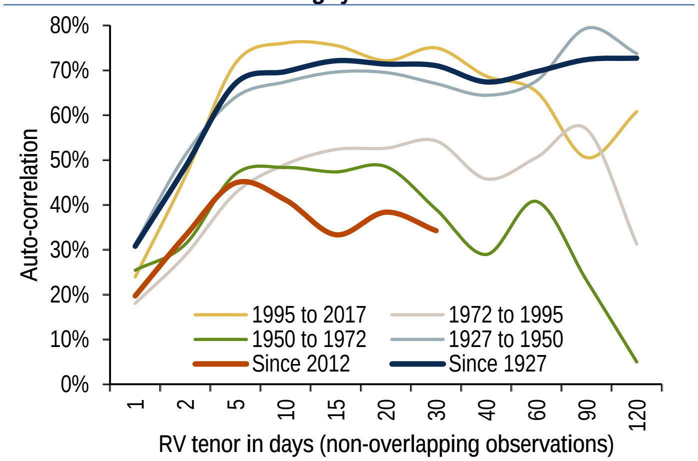
Focusing on the S&P, volatility auto-correlation has been a persistent phenomenon across historical volatility regimes (although it appears to be stronger during high vol periods, Chart 10) and time-frames (Chart 11). Moreover, vol auto-correlation has been less evident for very short term realised volatility tenors (less than 5 days) due to short term 'noise', which is reduced over the longer term.

Chart 10: The degree of S&P RV auto-correlation is evident across vol environments but is typically stronger in high vs. low vol regimes*



Source: BofA Merrill Lynch Global Research. Data: Dec-1927 to Apr-17.*Low (high) vol = times when trailing 1yr RV is below (above) the 25th (75th) percentile RV level of the entire period of 9% (27%).

Chart 11: While the absolute level of S&P RV auto-correlation can vary over time its nature has been largely similar over time

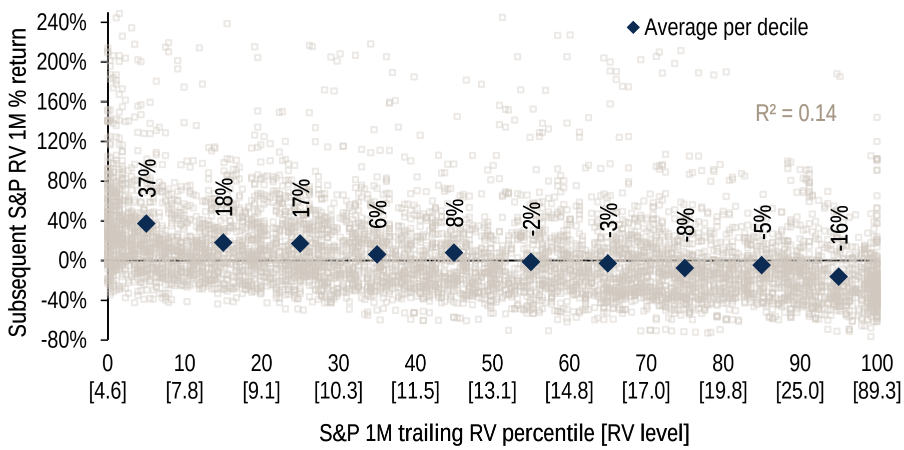


Source: BofA Merrill Lynch Global Research. Data: Dec-1927 to Apr-17.

Vol mean-reverts; pace of vol decay is a function of what led to the initial shock

Short term market forces can lead to extremely low or high volatility. However, while subsequent vol levels exhibit high auto-correlation to preceding levels of vol, short term vols eventually revert to longer term mean, particularly from unsustainably high or low vols (Chart 12).

Chart 12: Realised volatility % returns exhibit mean reversion. This means that RV tends to rise when RV is historically low and fall when RV is historically high

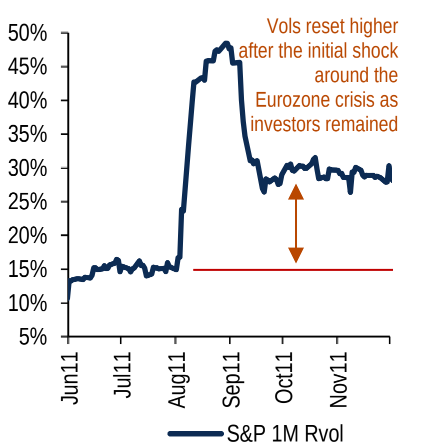


Source: BofA Merrill Lynch Global Research. Data:2-Jan-90 to 15-Sep-17.

While volatility eventually mean-reverts, it is often not obvious what the level of the mean is at any given point of time and over what time horizon it is mean-reverting. For instance, Chart 13 to Chart 15 illustrate how the level and pace with which vol decays following a spike can vary depending on the nature of the catalyst:

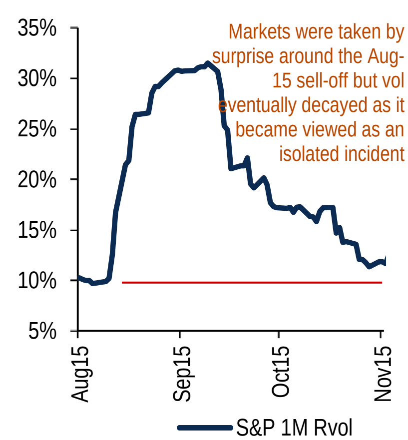
1. **Vol resets higher after the initial shock:** We witnessed such a scenario during the 2011 Eurozone crisis for instance, where the initial spike in vol faded but realised vol found a higher floor. This is typically the case when the risk catalyst is deemed systemic in nature.
2. **Vol resets to a similar level as before the shock:** This can happen either when the risk event is seen as an isolated incident (Aug15 for e.g.) or when volatility gradually decays (typically exponentially) over a relatively longer period of time as risk is slowly phased out (e.g. May10).
3. **Vol resets to a lower level following the spike:** Following the resolution of a well-flagged binary event (e.g. Brexit vote), vol can reset to a lower level. This is because uncertainty regarding the outcome dominates market sentiment in the lead up to the event. On the day of the event, markets quickly price in the scenario that materialises, which can cause a volatility spike. Following the initial reaction volatility can reset to a lower level as the event-driven uncertainty disappears.

Chart 13:Vol can reset higher after an initial shock (e.g., Eurozone crisis)



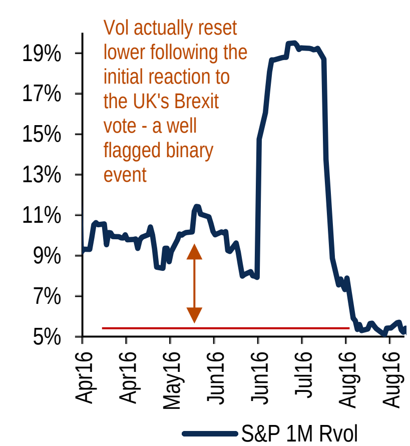
Source: BofA Merrill Lynch Global Research. Data: 1-Jun-11 to 30-Nov-11.

Chart 14: Vol can reset to a similar level as before the shock (e.g., Aug-15 sell-off)



Source: BofA Merrill Lynch Global Research. Data: 10-Aug-15 to 10-Nov-11.

Chart 15: Vol can reset to a lower level following the spike (e.g., Brexit vote)



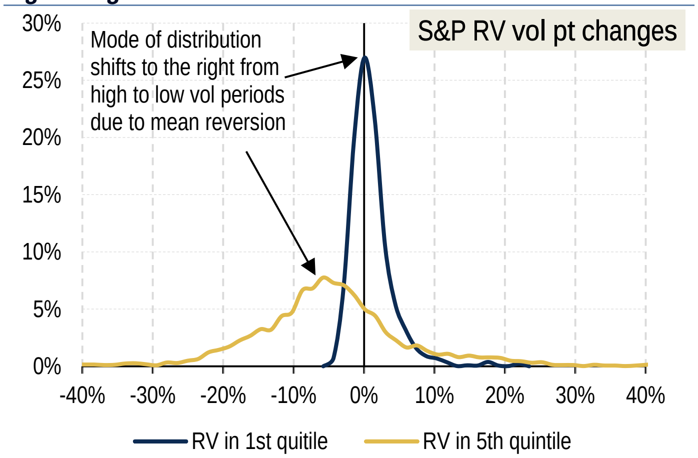
Source: BofA Merrill Lynch Global Research. Data: 1-Apr-15 to 1-Sep-15.

Realised vol changes tend to behave more like a ratio than a spread

We have shown that realised volatility (RV) is auto-correlated, meaning that future levels are dependent on past RV levels. Therefore, an investor attempting to anticipate the future level of RV can benefit from considering its current level. One such approach is to consider **vol point changes in RV**. The centre (mode) of the distribution of vol point changes remains dependent on the starting level of RV, which is consistent with our observations from Chart 12. More crucially however, so is its overall shape (or statistical moments, Chart 16).

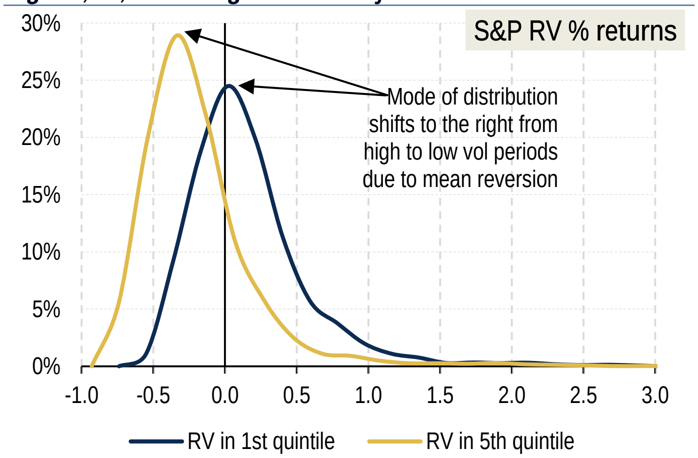
An alternative approach is to consider **RV % returns**: Here, the mode still reflects the tendency of RV to mean-revert, but the distribution for different starting levels of RV is significantly more 'stable' (or stationary in statisticians parlance) than in the case of vol point changes (Chart 17). In short, a 10% rise in RV (for e.g.) is similarly probable in both a low and high volatility environments (mean-reversion aside), while the same cannot be said for a 10 vol point rise.

Chart 16: RV vol pt changes behave dramatically differently in low vs. high vol regimes...



Source: BofA Merrill Lynch Global Research. Data: 30-Dec-1927 to 24-Aug-2017.

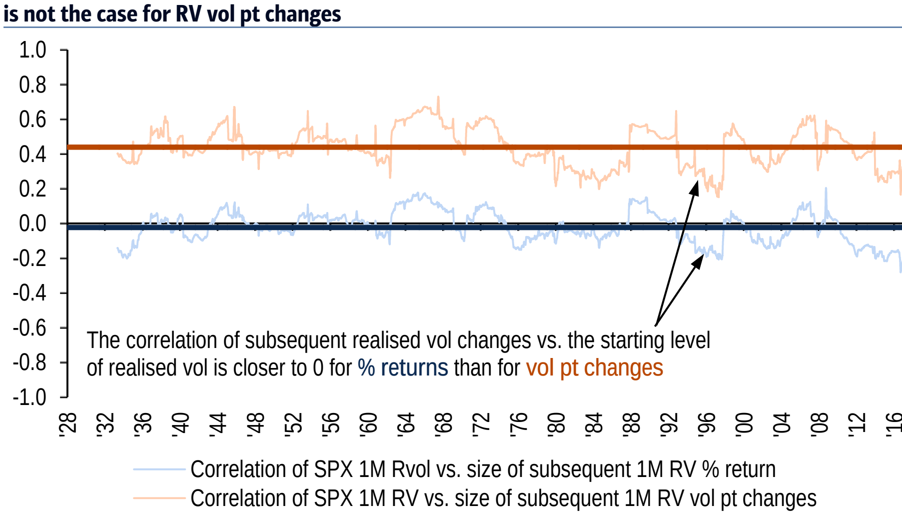
Chart 17: ...but RV % returns behave more consistently across vol regimes, i.e., considering RV % returns yields a more stable distribution



Source: BofA Merrill Lynch Global Research. Data: 30-Dec-1927 to 24-Aug-2017.

The benefit of considering RV % returns for investors is that they can maintain a relatively constant framework to view volatility over time. Indeed, Chart 18 shows that S&P 1m realised vol returns over time exhibit almost no correlation to the starting level of vol vs. >40% correlation for vol point changes. In the Appendix (Chart 64) we carry out a similar comparison of RV vol point changes to % returns for other assets.

Chart 18: S&P RV % returns are almost entirely independent of the starting level of realised vol. This is not the case for RV vol pt changes



Source: BofA Merrill Lynch Global Research. Data: 3-Jan-1928 to 27-Apr-2017.

To avoid over-relying on a specific path (rolling 5y windows since 1927) of a specific asset (S&P) we replicate this analysis on a diverse set of randomly generated GARCH(1,1) processes which are among the simplest volatility models embedding both auto-correlation and mean-reversion. We find that realised vol spread changes are consistently more correlated (on an absolute basis) to the starting level of volatility than vol returns for all processes which exhibit a reasonable degree of auto-correlation (i.e., where the impact of a shock on following days' returns is meaningful; Chart 19).

Chart 19: The lower dependence of RV % returns on the starting level of RV can also be seen in GARCH(1,1) models, removing the dependency of our result on a given asset or its price path.

Numbers are the differences between absolute correl of % vol returns vs. the starting level of vol and the absolute correl of vol pt changes vs. the starting level of vol (for most combinations of GARCH parameters , correl is lower for %vol returns)

alpha (impact of shock on following day's vol) \ Half-life (days)	1	16	31	46	61	76	91	106	121	136	151	166	181	196
1%	18%	14%	14%	17%	14%	9%	13%	18%	13%	18%	9%	14%	12%	10%
3%	18%	7%	8%	1%	4%	-6%	-3%	-4%	1%	-3%	0%	[illegible]	[illegible]	-2%
5%	6%	-1%	-6%	-8%	-8%	-9%	-12%	-10%	-10%	-16%	-12%	-13%	-16%	-13%
7%	11%	-7%	-11%	-14%	-4%	-19%	-20%	-24%	-21%	-18%	-28%	-24%	-28%	-27%
9%	11%	-18%	-20%	[illegible]	-23%	-28%	-28%	-22%	-32%	-23%	-32%	-28%	-35%	-34%
11%	7%	-22%	-20%	-24%	-25%	-28%	-25%	-25%	-29%	-34%	-37%	-31%	-33%	-40%
13%	10%	-19%	-25%	-32%	-38%	-34%	-34%	-28%	-33%	-37%	-34%	-34%	-25%	-27%
15%	4%	-25%	-27%	-32%	-28%	-35%	-34%	-29%	-33%	-31%	-37%	-31%	-38%	-38%

USDJPY SPX CL1 TY1

Source: BofA Merrill Lynch Global Research. Alpha & Half-life are GARCH parameters (each combination is to generate 50000 observations)

(Why) is there a Volatility Risk Premium?

- Empirical evidence points to robust x-asset vol risk premia over time
- When quantifying VRP, most often used IV-RV spread can be misleading
- Fundamentally, selling vol is like selling insurance
- VRP (like insurance premium) compensates for rare but large losses
- Portfolio vol requires further compensation for risk of correlated shocks
- Supply/demand dynamics can also influence amount of VRP on offer

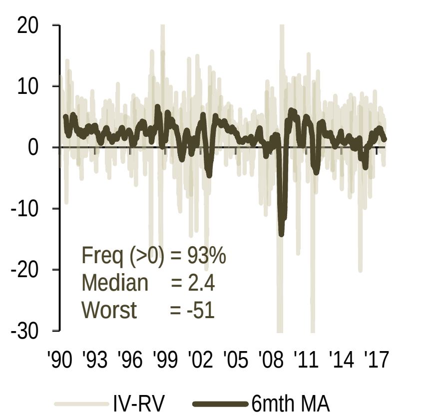
There is strong empirical evidence across multiple asset classes, regions and market instruments that – over the long run – the premium associated with selling volatility is both sizable and extractable. Here, we aim to answer two key questions: what exactly *is* the volatility risk premium (VRP) and *why* does it exist? In doing so, our main focus remains the S&P but a more cross-asset perspective is provided in the Appendix.

Quantifying VRP: most often used implied-realised vol spread can be misleading

The most straightforward and widely quoted measure of VRP is the *implied to realised volatility spread* (IV-RV). Here the implied volatility of (usually) an at-the-money (ATM) option is compared to subsequent realised vol of the asset over the life of the option. However, even though IV-RV is a convenient proxy for VRP, it is not directly accessible/tradable (in the next section we show that delta-hedging an ATM option yields an imperfect exposure to IV-RV).

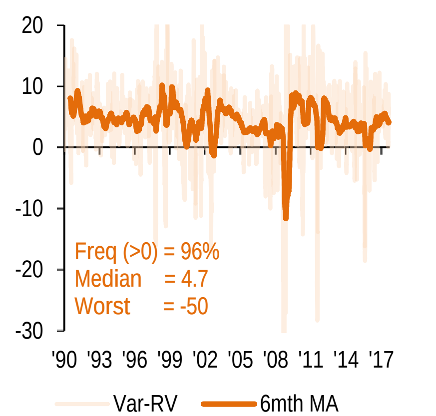
Another frequently quoted measure of VRP is the *implied VarStrike to realised vol spread* (Var-RV) which has been popularised with the advent of the VIX. But Var-RV is itself misleading as it benefits from the variance convexity premium (Chart 23) but does not accurately reflect the size of losses whenever realised variance (i.e., volatility squared) spikes. The fairest measure of VRP is therefore the *implied to realised variance* spread (Var^2-RV^2) as it accurately represents risk-reward and is tradeable for a wide range of assets. Chart 20 to Chart 22 compare these three measures of VRP for the S&P.

Chart 20: IV-RV underestimates both the frequency of gains and the size of losses



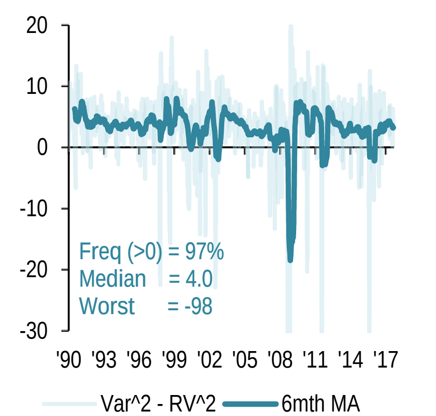
Source: BofA Merrill Lynch Global Research. Data: 3-Jan-90 to 15-Sep-17.

Chart 21: Var-RV overestimates the median VRP and underestimates losses



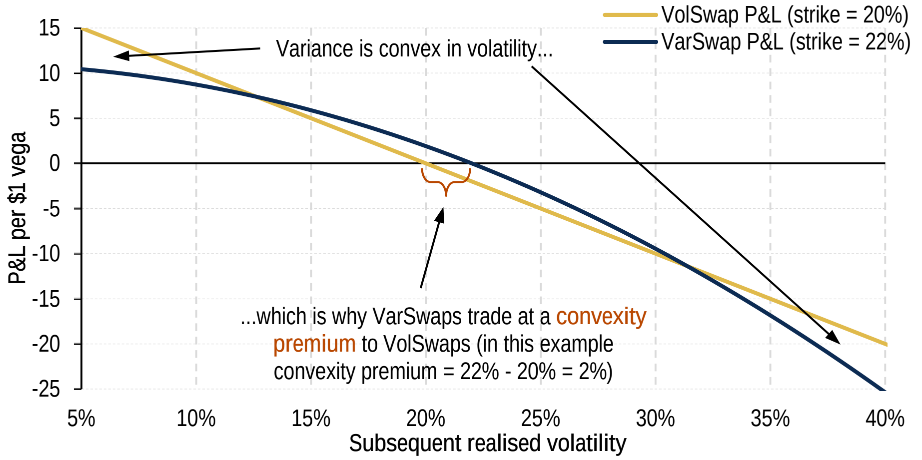
Source: BofA Merrill Lynch Global Research. Data: 3-Jan-90 to 15-Sep-17.

Chart 22: Var^2-RV^2 does not misrepresent risks or rewards as it is generally tradeable*



Source: BofA Merrill Lynch Global Research. Data: 3-Jan-90 to 15-Sep-17. *Sized by 1/(2 x Var) for easier comparison with IV-RV and Var-RV

Chart 23: Variance is convex in volatility: Gains are smaller & losses are larger for a short var trade. Consequently, the VarSwap strike trades at a convexity premium to the VolSwap strike

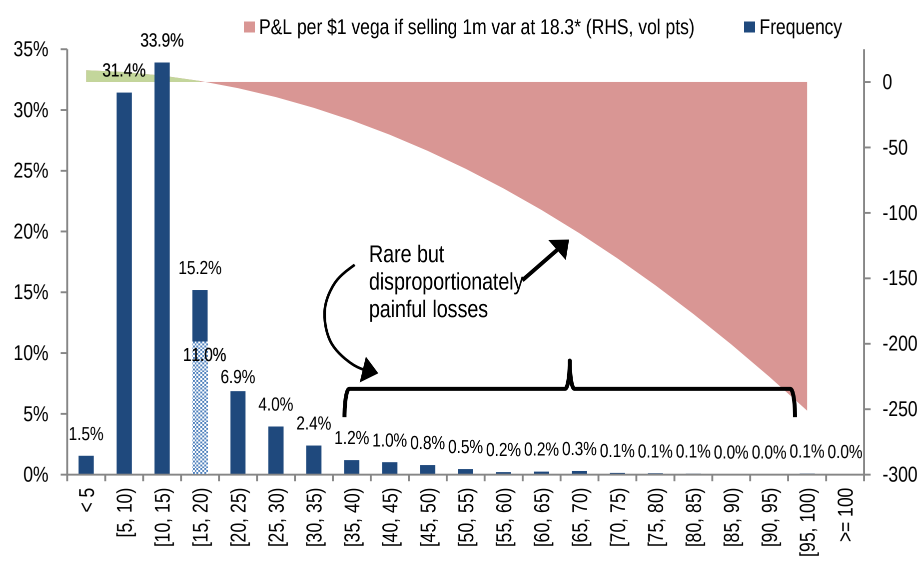


Source: BofA Merrill Lynch Global Research.

Why does vol risk premium exist?

From a fundamental perspective, option writing is analogous to selling insurance, with the option price or volatility implied from it being comparable to insurance premium. This is because option prices, much like insurance premia, need to compensate the seller for the risk of rare but large payouts. Indeed, as Chart 24 demonstrates, selling 1m variance on the S&P (at a long term average level) can have disproportionately large even if vanishingly rare losses. This argument holds whether we consider equities or indeed other asset classes, as volatility cannot fall below zero but has infinite upside.

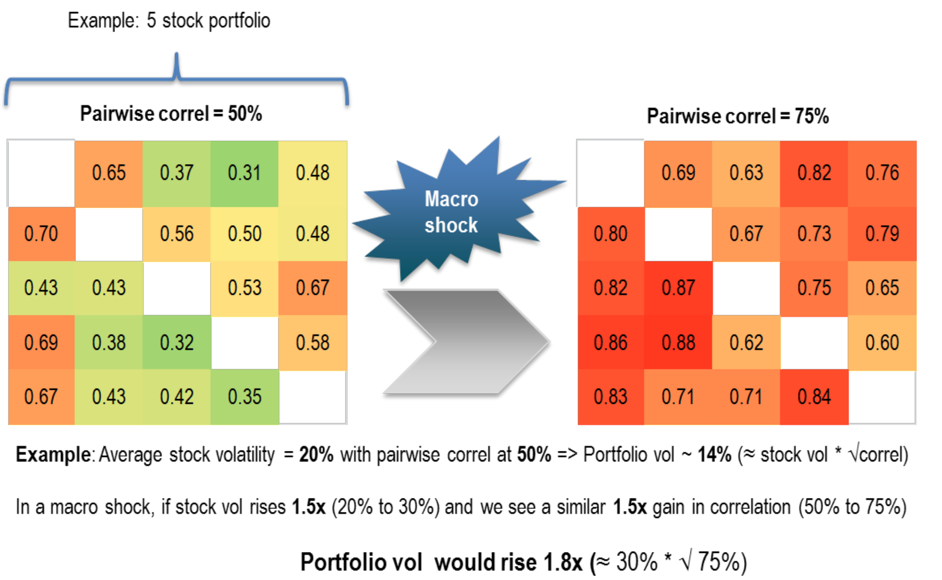
Chart 24: Fundamentally, volatility risk premium exists to compensate volatility sellers for the risk of disproportionately large, even if vanishingly rare, losses



Source: BofA Merrill Lynch Global Research. Data: Jan-1928 to Aug-17. *Median of VIX level (VXO before Jan-90) from Mar-86 to Aug-17. Shaded area for the [15,20)bucket represents the proportion of time realised vol was above 15 and below 18.3

Sticking however to the example of equities and in particular equity indices, we may further rationalise volatility risk premium from the perspective of compensation to the seller for the risk of a correlated shock to markets. As Chart 25 demonstrates, a rise in idiosyncratic (stock level) volatility coupled with a similar magnitude rise in correlation can lead to a disproportionately large rise in portfolio volatility

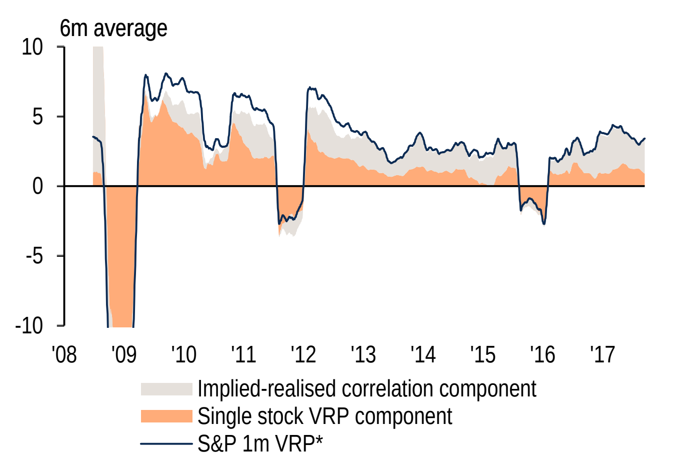
Chart 25: Index or portfolio vol requires compensation for the risk of a correlated macro shock



Source: Source: BofA Merrill Lynch Global Research

In fact, given that equity index volatility is a function of stock volatility and correlation, we may deconstruct equity index volatility risk premium into stock volatility risk premium (compensation for idiosyncratic risk) and correlation risk premium (compensation for a macro-led correlated shock). Chart 26 shows how much of the S&P implied to realised variance spread can be attributed to idiosyncratic and correlation risk over time. Notably, over the last two years the implied to realised correlation risk premium contributed approx. 70% of the S&P 1m VRP.

Chart 26: S&P VRP has lately been driven more by the implied-realised correlation premium than single stock VRP



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-08 to 15-Sep-17.*The difference between S&P 1m VRP and the two stacked regions amounts to the error in approximating correlation using the formula on the right.

The following relationship is true for both implied and realised volatility and correlation:

$$IndexVol^2 \approx Correl \times AvgSingleStockVol^2$$

We can therefore decompose S&P VRP as follows:

$$\boldsymbol{K_I^2 - \sigma_I^2 \approx \rho \times (K_{avg}^2 - \sigma_{avg}^2)} + K_{avg}^2 \times (\tilde{\rho} - \rho)$$

where K_I and K_{avg} are the S&P and average single stock vols, respectively (and similarly for realised vols σ_I and σ_{avg}) and ρ and $\tilde{\rho}$ are the realised and implied index correlation.

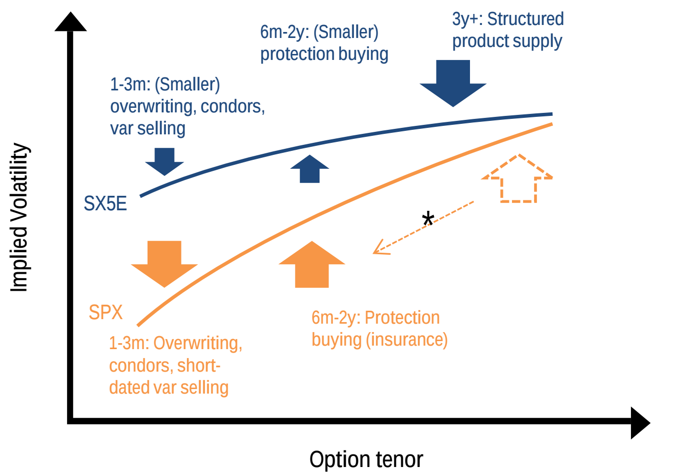
The supply and demand perspective

Setting aside the fundamental justification for volatility risk premium, supply demand imbalances in option markets can play a big role in deciding the extent of the premium and how it evolves. These imbalances vary across asset classes but also across markets within an asset class. For instance, Chart 27 shows that the forces of supply and demand on the two most liquid equity index derivatives markets globally (S&P & ESTX50) can be quite different.

While institutional demand for hedging equity holdings tends to push implied volatility and skew higher in most equity indices, the ESTX50 index options market (particularly in low rates environments) sees significant retail supply of long-dated volatility through yield enhancement products. Meanwhile the S&P option market instead sees demand from insurance companies hedging annuity products. This difference in flows has tended to support the steepness of the S&P volatility term-structure relative to that of the ESTX50 and also contributes to why S&P vol risk premium is often one of the most attractive to harvest.

Chart 27: Within equities, the supply-demand forces that drive volatility risk premium can vary for different regional markets

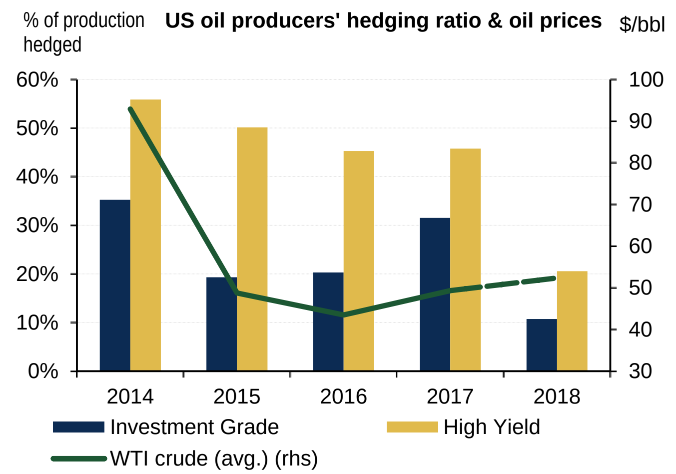
SX5E long-dated options tend to see supply pressure from retail investors while S&P long-dated options see demand from insurance companies



Source: BofA Merrill Lynch Global Research. *In recent years, long-dated S&P protection buying flows from insurance companies have migrated to the middle part of the curve

Chart 28: Producer hedging flows create demand for options on crude oil

While producers generally use both linear and convex instruments to hedge, the fraction of options usage has been upwards of 40% of their total hedging in recent years



Source: BofA Merrill Lynch and company reports. Data as of the end of Q2 2017

Another example of supply demand imbalances can be seen in commodity markets like crude oil options (see our extensive Commodity Volatility Primer). Option demand from both oil producers (for oil puts) and consumers (e.g. Airlines, for oil calls) can boost the crude oil volatility risk premium (Chart 28 shows the proportion of oil production that is hedged by US producers via swaps and options through time). This demand is in turn offset by speculators who provide liquidity. Similarly in agriculture, consumers (e.g., livestock farmers, big food manufacturers) and producers (farmers) buy options to hedge their price exposure, which boosts the volatility risk premium.

In currency and rates markets, corporate and institutional liability hedging programmes can create demand for options that boosts the volatility risk premium (in selected option tenors and tails for rates). In all these cases, it is important to identify and understand the nature and evolution of structural flows that can create imbalances and impact the volatility risk premium.

Harvesting the Volatility Risk Premium

- Variance & volatility swaps provide the cleanest exposure to VRP
- Delta-hedged options are path-dependent but listed & customizable
- Next-gen var (replication) products offer both clean & listed exposure
- S&P 1m var selling had 3x Sharpe & 2x Calmar vs. long S&P since '01
- Ratio-sized short var has higher Sharpe & lower losses vs. fixed % vega
- Selling short-dated var preferable despite higher VRP in longer tenors

Exposure to VRP & efficiency of extracting it varies across implementations
There are several alternatives for accessing VRP, ranging from listed option strategies (selling calls, puts, straddles or strangles) to OTC swap-based strategies (selling volatility or variance swaps). However, exposure to VRP and the efficiency of extracting it can vary substantially. Also, factors such as liquidity, transparency, cross-asset applicability etc. can play a big role in an investor's choice of implementation for capturing VRP.

Variance swaps provide clean exposure to VRP, while delta-hedged option strategies can suffer from path dependency and be operationally intensive to implement. However, the latter benefit from the transparency of exchange-traded markets and also allow for greater customization of VRP exposure. From a risk perspective, while variance swaps have a convex exposure to vol spikes (Chart 23), highly volatile, mean reverting markets around the option strike can lead to more adverse outcomes for delta-hedged option strategies. Meanwhile, even as non-delta-hedged option strategies have only an indirect exposure to VRP, they allow investors to embed their views on asset mean-reversion into the strategy. Table 1 summarises some key trade-offs between implementations.

Table 1: Trade-offs of exposure to VRP using different implementations

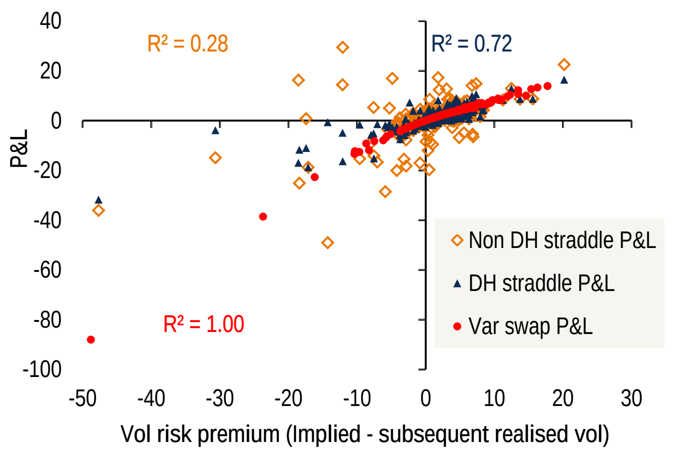
Instruments	Risk premium exposure	Conditions for positive P&L	Pros	Cons
Variance swaps	Implied-realised variance (vol squared)	Implied VarStrike > realised volatility	Clean exposure to VRP; higher strike than Volatility swaps	OTC (non-transparent); convex exposure to vol spikes
Volatility swaps	Implied-realised volatility	Implied VolSwap strike > realised vol	Clean exposure to VRP	OTC (non-transparent); heavily model-dependent pricing; lower strike than VarSwaps
Delta-hedged straddles/strangles	Path dependent implied-realised vol (scaled by gamma)	Low realised volatility around the strike (high gamma region)	Tailored (delta-hedge program) & targeted (custom strike) exposure to VRP; listed, liquid instruments across asset classes	Imperfect exposure to VRP (path dependent P&L); additional delta-hedging execution cost, operationally intensive
Non delta-hedged straddles/strangles	Implied-realised volatility, spot mean-reversion	Underlying unlikely to move significantly away from the strike	Targeted (custom strike) exposure to VRP; uses listed, liquid instruments across asset classes	Indirect exposure to VRP (P&L purely dependent on the underlying level at expiry)
Corridor variance swaps	Implied-realised variance (vol squared); and accrues no realised vol outside a pre-defined strike range	Implied vol > realised vol when the spot is within the strike range & the underlying spends limited time in the range	Custom but clean exposure to VRP	OTC (non-transparent); convex exposure to vol spikes (potentially less than full VarSwap); lower strike than VarSwaps
Conditional variance swaps	Implied-realised variance (vol squared); has no exposure to the VRP outside a pre-defined strike range	Implied vol > realised vol when the underlying remains within the chosen strike range	Custom but clean exposure to VRP; allows investors to take a view on VRP within a specific spot range	OTC (non-transparent); convex exposure to vol spikes
Listed VarSwap replication*	Implied-realised variance (volatility squared)	Implied vol > realised vol, provided underlying remains within the chosen strike range	Clean exposure to VRP using listed, liquid instruments across asset classes	Operationally intensive; lower VRP than OTC VarSwap

Source: BofA Merrill Lynch Global Research.*See: More to variance swaps than meets the eye and How to profit from QE failure in Japan with positive carry.

One relatively non-standard alternative for capturing VRP highlighted in Table 1 is the listed replication of variance swaps, which involves using liquid, listed underlying options to mimic a variance swap's payoff. The structure takes the best of both worlds in that it provides a variance swap's relatively cleaner exposure to VRP while using listed options for a more transparent implementation. For more details on the pros & cons (risks) of such implementations, please refer to [More to variance swaps than meets the eye] and [How to profit from QE failure in Japan with positive carry].

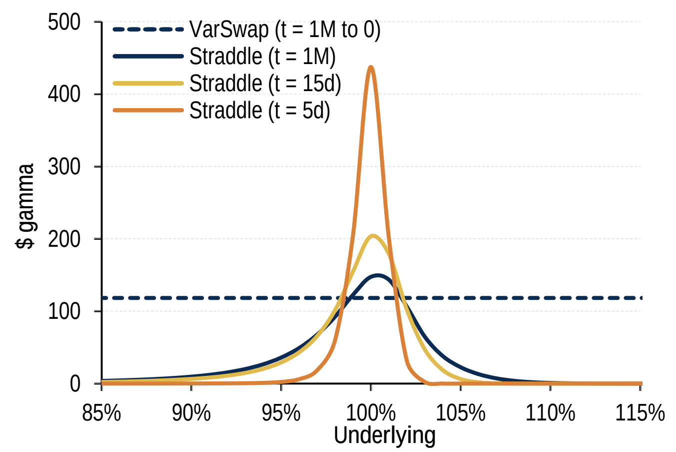
VarSwaps are fully exposed to VRP; DH (non DH) straddles 3/4th (1/4th)-exposed
Variance swaps provide a clean exposure to VRP while the P&L of delta-hedged straddles is path dependent and non-delta hedged straddles only have an indirect exposure to VRP (Chart 29). The difference in exposure between variance swaps and straddles can be explained via Chart 30 which shows that while the gamma of straddles is sensitive to the underlying spot level, variance swaps have constant dollar gamma exposure. As a result, while variance swap P&L is only dependent on the implied variance strike and subsequent realised vol, the P&L of delta hedged straddles can vary significantly depending on where the realised volatility is accrued (highest sensitivity closest to the strike, particularly when closer to the expiry).

Chart 29: VarSwaps offer a pure exposure to VRP but short (delta-hedged) straddles are path dependent with varying exposure to VRP…



Source: BofA Merrill Lynch Global Research. Data: 18-Jan-01 to 21-Jul-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 30: …the VRP exposure of (delta-hedged) straddles depends on the level of the underlying throughout the life of the trade



Source: BofA Merrill Lynch Global Research.

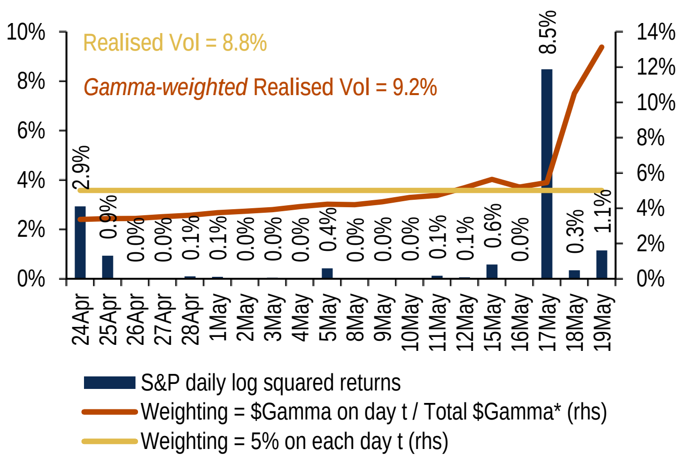
It can be shown that the P&L of delta-hedged straddles can almost entirely be explained by implied vol minus (subsequent) *gamma-weighted realised vol* (see the formula below and Chart 31 and Chart 32). That said, the P&L of a delta-hedged option strategy is highly model-dependent and there are several levers that investors can pull to fine-tune their exposure, e.g. what vol to delta-hedge with (running IV, fixed IV?), how often to delta-hedge (daily, weekly?) and when to delta-hedge (at close, intra-day?). We intend to discuss several such considerations in a future publication focussed on delta-hedged option strategies.

$$DH\ P\&L \approx \frac{1}{2} Total\ \$Gamma \times [Ivol^2 - GwRvol^2]$$

$$\text{Where } Total\ \$Gamma = \frac{T}{252} \times \sum_{t=1} \Gamma_{t-1}^{\$}$$

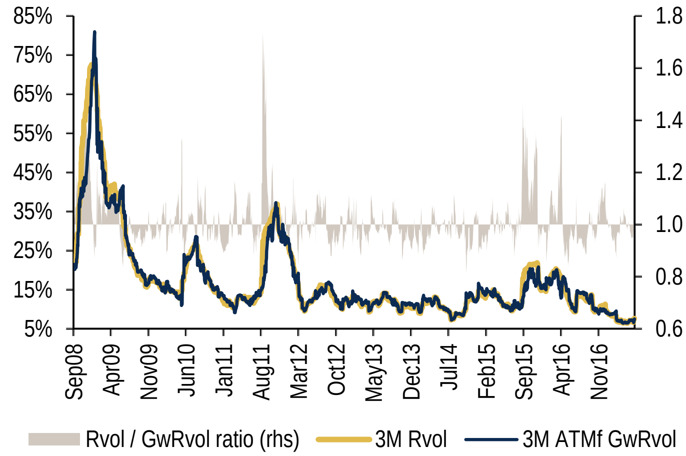
$$\text{and } GwRvol^2 = \frac{1}{Total\ \$\ Gamma} \times \sum_{t=1} \Gamma_{t-1}^{\$} \ln\left(\frac{S_t}{S_{t-1}}\right)^2$$

Chart 31: Gamma weighted RV is a variation of RV where log squared returns are weighted by gamma (rather than being equally weighted)



Source: BofA Merrill Lynch Global Research. Data: 24-Apr-17 to19-May-17.*$Gamma of an option expiring on 19-May-17 with strike K = level of S&P on 24-Apr-17.

Chart 32: Gamma weighted RV is not dissimilar to RV over the long term but can vary substantially over shorter time scales



Source: BofA Merrill Lynch Global Research. Data: 1-Jan-08 to 23-May-17.

For the remainder of this publication, we focus our analysis on variance swaps to examine the historical behaviour of VRP, the impact of different sizing methods/roll schedules/maturity considerations and to demonstrate the effectiveness of short volatility strategies in a multi-asset traditional or risk premia portfolio.

As a quick reminder,

$$\boldsymbol{P\&L\ of\ a\ VarSwap = N \times (K^2 - \sigma^2)},\quad \text{where}\quad \boldsymbol{N = \frac{vega}{2K}}$$

Where, N = Variance units or variance notional, K = implied variance strike, σ = realised volatility and *vega* = vega notional

Robust performance of hypothetical short S&P 1m var strategy since 1990s

We create hypothetical time series of systematically selling 1m S&P variance swaps since the 1990s. For illustrative purposes, the strategy is sized such that $0.2 vega of a 1m VarSwap is sold per $100 of portfolio notional at every monthly listed option expiry (accounting for indicative transaction costs). While BofAML proprietary VarSwap data allows us to mark-to-market the strategy daily since 2001, we extend the time series going back to the 1990s using monthly spot data for the VIX[3]. We show the back-tested performance and key statistics of the strategy in Chart 33 and Chart 34. Note the performance statistics shown in Chart 33 only correspond to daily data since 2001.

Short S&P 1m var strategy has ~3x Sharpe & 2x Calmar vs long S&P since 2001

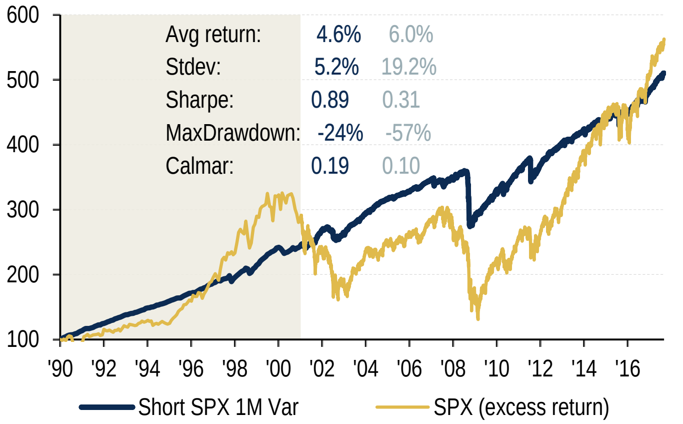
Systematically selling S&P 1m variance swaps has been a fairly robust and profitable strategy, which has outperformed long equities on a risk-adjusted basis. The strategy has Sharpe & Calmar ratios of 0.9 & 0.2 respectively, which are ~3x & ~2x versus the S&P[4]. A closer examination of the short 1m var strategy reveals a more skewed and fat-tailed return distribution versus a long equity position.

[3] The VIX spot data only allows us to generate monthly time series (and not daily) since it corresponds to a constant tenor S&P500 30-day variance swap. Moreover, please note that since VIX uses calendar day quoting convention, we adjust the levels to business day convention using methodology highlighted in Demystifying the VSTOXX futures kink

[4] We use data since 2001 to make any remarks on the strategy performance since daily mark-to-market considerations are a crucial element of the risk embedded in short VarSwap strategy.

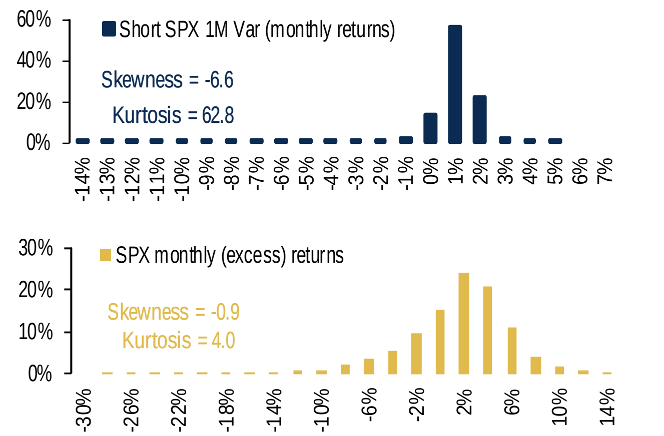
Chart 33: A hypothetical back-tested short S&P 1m var strategy (vega = 0.2%) would have generated ~3x the Sharpe & 2x the Calmar vs. long S&P since 2001

Monthly observation points from 1990 to 2001 (shaded region). Statistics are for the period since 2001 where daily observations are available



Source: BofA Merrill Lynch Global Research. Data: 17-Jan-90 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 34: Short S&P 1m variance returns are more skewed and fat tailed than S&P returns



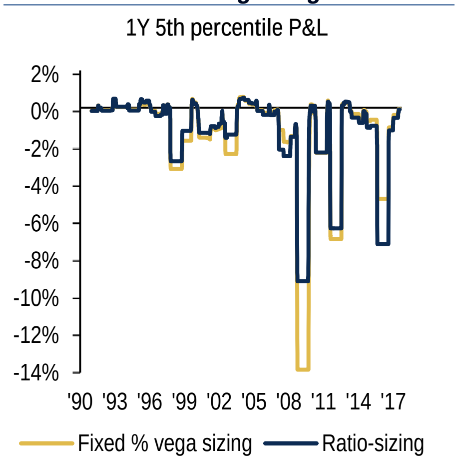
Source: BofA Merrill Lynch Global Research. Data: 22-Jan-01 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Prefer vol-ratio sizing over fixed %-vega sizing in short var strategies

Chart 33 and Chart 34 assume fixed %-vega sizing (which is the approach usually taken in short var implementations), where variance swap vega sold is purely a function of portfolio notional and is agnostic to the prevailing vol regime. However, as highlighted earlier, future realised vol changes are dependent on the level of trailing realised volatility itself and that the distribution of percent changes in realised vol is more stable (through time) than that of the spread changes. It follows from there that a short variance strategy where vega exposure is inversely proportional to the level of vol is likely to exhibit a more consistent/stable behaviour.

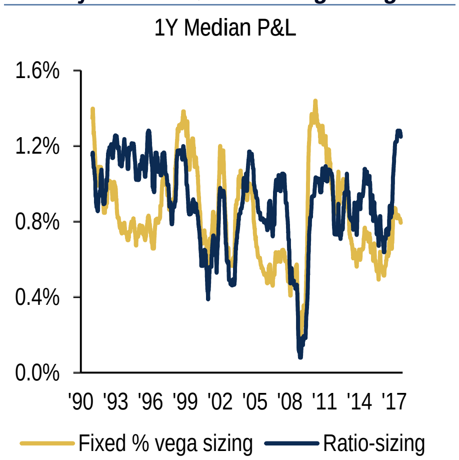
Chart 35 to Chart 37 show the hypothetical expiry P&L of selling S&P 1m var on a daily basis, illustrating how extremely positive and negative returns (as well as median P&Ls) are more consistent over time in the case of ratio-sizing vs. fixed %-vega sizing.

Chart 35: Large losses are more similarly sized for ratio- vs. constant vega sizing...



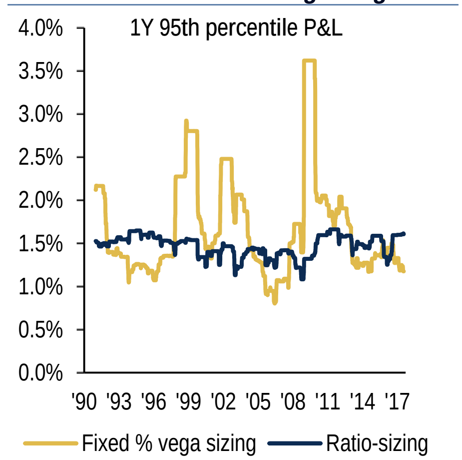
Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 36:...while the median P&L behaves similarly for ratio- & constant vega sizing...



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 37:...and large gains are again more stable for ratio- vs. constant vega sizing

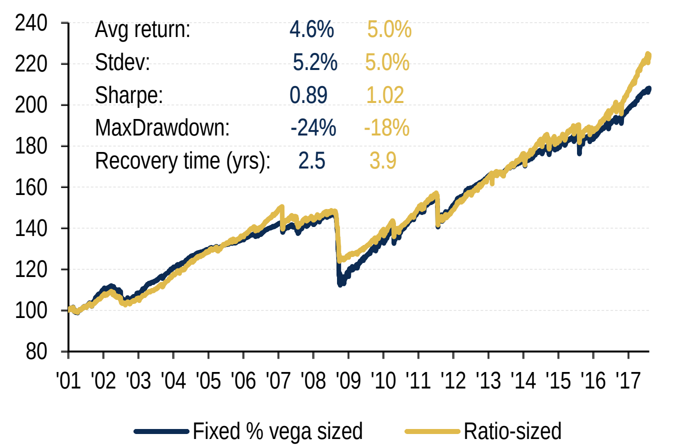


Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

In Chart 38 and Chart 39, we compare the performance of systematically selling S&P 1m var with fixed %-vega (0.2%) versus a variation where vega is scaled inversely with the level of the VarSwap strike (ratio-sizing). The %-vega for this variation is given by leverage * 20/ VarStrike, where leverage = 0.2 in this case.

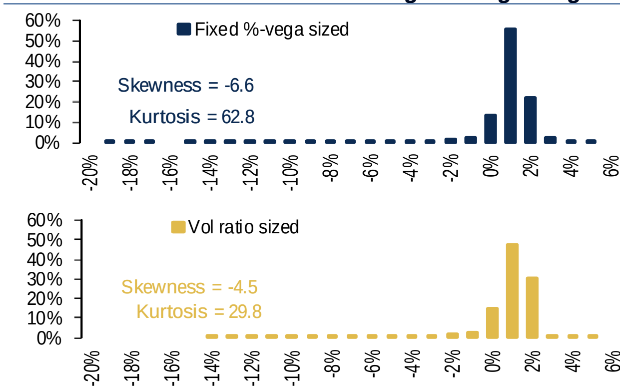
From the charts, we note the robust back-tested results of the ratio-sized strategy with a higher Sharpe ratio as well as lower drawdowns versus the fixed %-vega sized strategy. Moreover, as expected the strategy return distribution demonstrates lower skew and kurtosis in the case of ratio-sizing thus reflecting the more stable nature of the %-return distribution. However, it is worth noting that the recovery time for the ratio-sized strategy is longer.

Chart 38: Sharpe & Calmar ratios of short S&P 1m var are higher in the case of ratio-sizing vs. % vega sizing, but the recovery time is longer



Source: BofA Merrill Lynch Global Research. Data: 19-Jan-01 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 39: The returns of short S&P 1m var are less negatively skewed and less fat-tailed in the case of ratio-sizing vs. % vega sizing



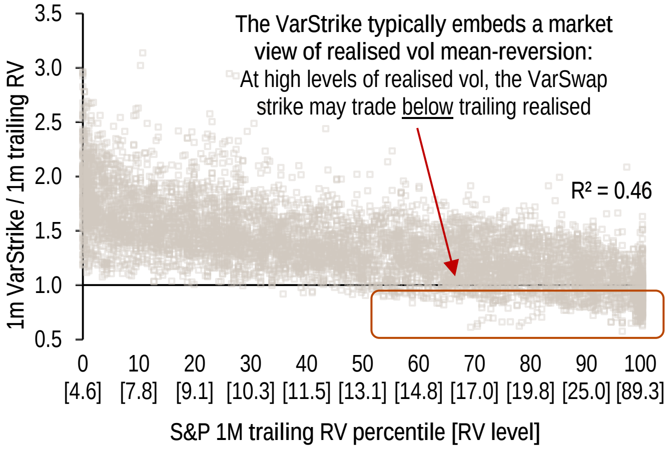
Source: BofA Merrill Lynch Global Research. Data: 19-Jan-01 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

VarSwap prices already embed a view on RV mean-reversion

In the previous section we noted that realised volatility exhibits mean-reversion in the sense that periods of ultra-high or low realised vol are not expected to be sustained indefinitely. Unsurprisingly, market-makers are cognizant of this behaviour and account for it in the pricing of VarSwaps (and implied volatility in general): VarSwap strikes tend to trade at a smaller premium – or even a discount – to trailing RV when RV is high vs. its own history (Chart 40).

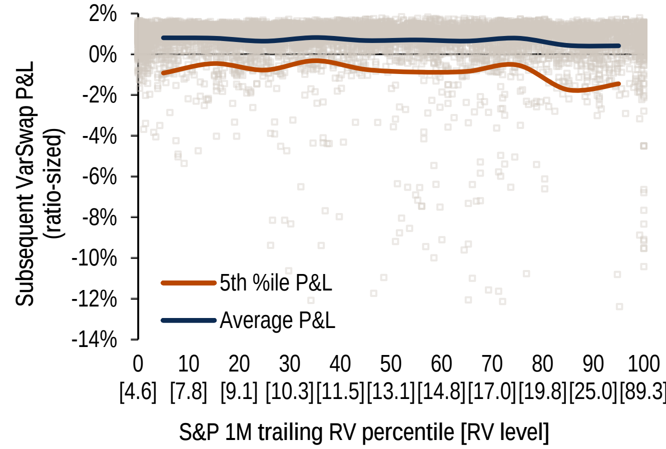
However, there is no discernible impact of VarSwap strikes embedding vol mean reversion on average profitability or losses across vol regimes (Chart 41). In other words, realised volatility tends to mean revert faster than what is priced into VarSwaps. Moreover, it is interesting to note from Chart 41 that the average back-tested returns of a ratio-sized short var strategy do not vary much across volatility regimes, which isn't the case for a fixed % vega sized short var strategy.

Chart 40: S&P VarSwap prices can trade below current RV when RV is exceptionally high embedding a view that RV will mean-revert lower…



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17.

Chart 41:… however, there is no discernible impact of VarSwap strikes embedding vol mean reversion on average P&L of short var across vol regimes



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17.

How much leverage should one have in a short variance strategy?

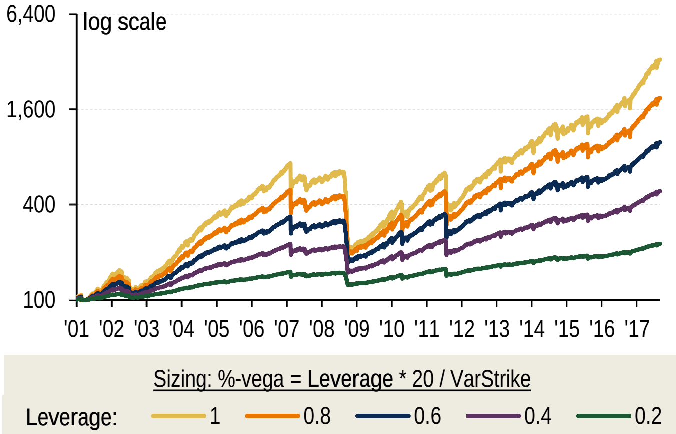
While our choice of 0.2% vega sizing was somewhat arbitrary, a natural question when allocating to short volatility systematically is: how much leverage should one have? Despite the apparent simplicity of the question the answer is somewhat elusive. While a very low leverage would not have enough exposure to the VRP, a very high leverage would be associated with higher drawdowns (i.e. tail risk). In the end, the desired short vol exposure is likely to be a function of investor's target return or acceptable level of losses based on historical evidence rather than a universally optimal sizing.

As an illustrative example, consider the same systematic strategy of selling 1m variance (ratio-sized) once a month but vary the degree of leverage per $100 of portfolio from 0.2 to 1 (recall, %-vega for ratio-sized strategy is given by leverage * 20/ VarStrike). We note from Chart 42 and Table 2 that:

1. As expected, the annual return, standard deviation and max drawdown increase as the leverage increases.
2. However, the Sharpe ratio remains constant when calculated using monthly observations on rebalancing dates. It is worth noting though that the Sharpe ratio based on daily data reduces with increasing leverage, i.e. the daily fluctuations increase on adding leverage.
3. It is also interesting to note that Calmar ratios improve with an increase in leverage albeit at the expense of longer recovery times

All said, we prefer a leverage of 0.2 in the ratio-sized strategy as it balances attractive risk-adjusted returns with a tolerable drawdown profile.

Chart 42: Leverage is a key consideration in allocating to short var



Source: BofA Merrill Lynch Global Research. Data: 19-Jan-01 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance.

Table 2: Higher leverage to short var keeps Sharpe ratios fairly constant & increases Calmar ratios but at the expense of longer recovery times

Leverage →	0.2	0.4	0.6	0.8	1	S&P500
Ann. return	5.0%	10.1%	15.1%	20.1%	25.2%	6.0%
Volatility	4.9%	10.1%	15.4%	21.1%	27.4%	19.2%
Sharpe (daily)	1.02	1.00	0.98	0.95	0.92	0.31
Sharpe (monthly)*	1.03	1.03	1.03	1.03	1.03	0.33
Max Drawdown	-18%	-34%	-49%	-63%	-74%	-57%
Calmar	0.28	0.29	0.31	0.32	0.34	0.10
Recovery time (yrs)	3.9	4.1	4.2	5.6	5.9	6.1
Avg. vega per $100	0.24	0.47	0.71	0.95	1.18	-

Source: BofA Merrill Lynch Global Research. Data: 19-Jan-01 to 15-Sep-17. Sizing: %-vega = Leverage * 20 / VarStrike. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance.

Is it more attractive to sell longer dated variance versus shorter dated?

Intuitively, we should expect longer-dated var to embed a higher risk-premium vs. short-dated var on account of the increased difficulty in predicting the behaviour of realised vol further into the future. This *term premium* (TP) is typically evidenced by an upward sloping volatility term-structure in benign markets. However, the key question is whether this additional (term) premium actually translates to an improved risk-reward profile for selling 1y var compared to, say, 1m var.

Comparing short var across tenors? Size for equal realised var contributions

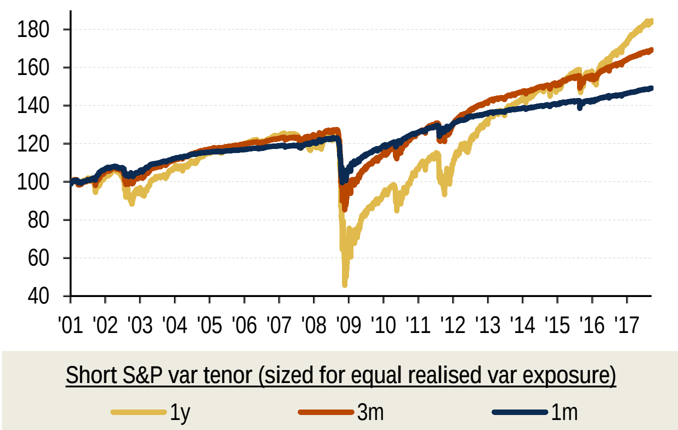
In order to compare a short var strategy across tenors, we size such that the realised var contribution to the P&L (i.e. var units x realised variance) is the same across tenors for the same holding period. As a result, the difference in performance across different tenors is only a function of how implied variance is priced through time. As highlighted in Chart 43, the back-tested results vary quite significantly across tenors.

Short-term var offers better risk-reward despite more premium in long-term var

Table 3 highlights higher average return & standard deviation for the strategy that systematically sells longer-dated var vs short-dated. However, the rise in standard deviation & max drawdowns far exceeds the increase in average return, making selling long-dated var less attractive, on a risk-adjusted basis. Moreover, the recovery time for selling long-dated variance is also significantly higher. On average, selling short dated var therefore outperforms on a risk-adjusted basis across regimes vs longer dated var.

A steeper term structure since '09 has boosted risk-reward for shorting S&P medium term var. It is interesting to note that the relatively higher term premium that has been on offer in S&P post 2009 vs pre-GFC has made short 3m var relatively more attractive since then (see Chart 66). Intuitively, in the absence of significant equity drawdowns (i.e. no term structure regime change), shorting longer dated variance can be expected to outperform shorter dated var. The challenge however is to anticipate the persistence of such a regime.

Chart 43: Short S&P 1m, 3m & 1y (staggered monthly for >1m tenor) behave differently even when sized such that the realised var P&L contribution (i.e., var units * realised variance) is constant



Source: BofA Merrill Lynch Global Research. Data: 19-Jan-01 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Table 3: Systematically selling short dated variance has offered better risk-reward historically despite longer-dated variance pricing in a higher risk premium

Statistics	1m	3m	1y
Ann. return	2.5%	3.4%	5.1%
Volatility	4.0%	6.9%	16.4%
Sharpe	0.62	0.49	0.31
Max Drawdown	-19%	-33%	-64%
Calmar	0.13	0.10	0.08
Recovery time (yrs)	2.1	2.6	5.5

Source: BofA Merrill Lynch Global Research. Data: 19-Jan-01 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Why is short 1y var so much riskier than 1m var, despite having same exposure to the realised variance? The significant difference in risk characteristics (as measured by standard deviations or max-drawdowns) across different tenors may seem surprising. We therefore take a closer look into understanding the factors driving the short var P&L below, which helps us understand this behaviour.

Performance attribution of short var into Term P&L and VRP P&L

We decompose the (expiry) P&L of a short S&P 1y var trade, sized for 1 var-unit, into:

1. **Term P&L:** The difference between the square of the 1y var strike and the sum of the square of 1m var strikes for 12 monthly trades entered over the course of the year (each sized for 1/12 var units), and

2. **Aggregate 1m VRP P&L**: The cumulative P&L of 12 short 1m var trades (entered once a month over the course of the year, each sized for 1/12 var units).

Mathematically, this can be expressed as:

$$K_{0,12}^2 - \sigma_{0,12}^2 = \left(K_{0,12}^2 - \frac{1}{12}\sum_{m=0}^{11} K_{m,m+1}^2\right) + \frac{1}{12}\sum_{m=0}^{11}\left(K_{m,m+1}^2 - \sigma_{m,m+1}^2\right)$$

where, $K_{m,n}$ is the strike of a variance swap traded in month *m* that expires in month *n* and $\sigma_{m,n}$ is the realised volatility between *m* and *n*.

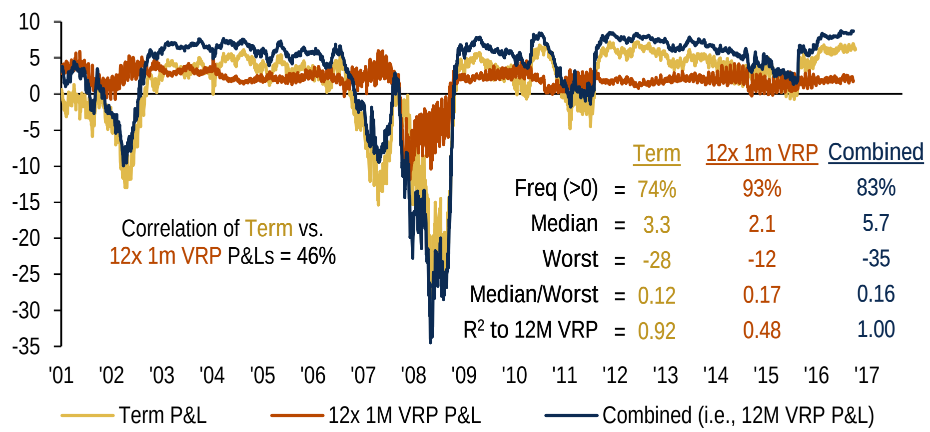
We note that:

- **All parts of the above decomposition are in practice tradable** since the first (blue) and third (red) components are just a combination of different variance swaps. Importantly though, the Term P&L (2nd component, in yellow) is purely given by changes in implied variance strike, i.e., it has no exposure to realised volatility.

- **Term P&L is the largest driver of short 1y VarSwap P&L on average**, better explaining it by a factor of approximately 2x versus the aggregate 1m VRP P&L (Chart 44).

- **The aggregate 1m VRP P&L has a better risk-adjusted P&L profile versus the Term component.** This can be seen in Chart 44 by the 20% greater frequency of positive returns or 1.5x better risk-adjusted returns (as measured by median gain to worst loss ratio). It is also worth noting that the two components are very well correlated (46% on an expiry basis) & therefore offer limited diversification benefit when put together (as is the case for 1y var). Indeed, the back-tested risk-adjusted returns of short 1y var lie somewhere in between these two components. This suggests that *Term P&L* did not improve (in fact reduced) the superior risk-adjusted returns of the *Aggregate 1m VRP* component.

Chart 44: The back-tested risk-reward of short S&P 1y var lies somewhere between that of the *Term* component (implied to implied exposure) and the *Aggregate 1m VRP* component



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-01 to 9-May-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

While the above approach highlights the greater value in systematically selling shorter-dated S&P var on a hold-to-expiry basis, in what follows we also look to explain the source of poor performance of longer dated var from a daily mark-to-market (MtM) perspective.

Performance attribution of short var into implied and realised P&L

We decompose the systematic short S&P 1m and 1y var strategies into:

1. **Accrued (realised) P&L:** We construct a hypothetical time series of systematically selling 1m and 1y var , where only the accrued (realised) P&L is captured (yellow lines in Chart 45 and Chart 46)

2. **Implied (mark-to-market) P&L**: Here, we create a hypothetical time series of systematically selling 1m and 1y var, where only the implied mark-to-market P&L is captured (blue lines in Chart 45 and Chart 46).

Mathematically, this can be expressed as:

$$\boldsymbol{VarSwapP\&L_t} = \boldsymbol{N} \times \left[\frac{t}{T} \times \left(K_{0,T}^2 - \sigma_{0,t}^2\right) + \frac{T-t}{T} \times \left(K_{0,T}^2 - K_{t,T}^2\right)\right]$$

Where, N = Var units traded, T = VarSwap tenor, t = time elapsed since the initiation of the trade, $K_{0,T}$ is the traded variance swap strike, $\sigma_{0,t}$ is the realised volatility till time t and $K_{t,T}$ is the swap strike of variance swap at time t that expires at time T.

In other words,

$$\boldsymbol{VarSwapP\&L_t} = \boldsymbol{Accrued\ P\&L_{o.t}} + \boldsymbol{Implied\ P\&L_{t,T}}$$

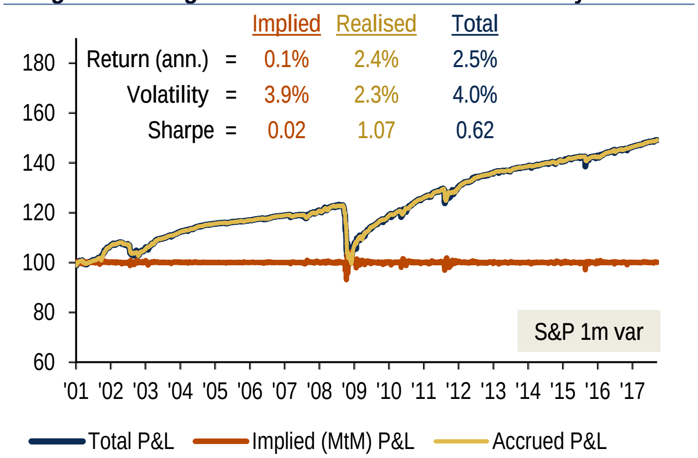
From Chart 45 and Chart 46, we note that:

- **The above decomposition is hypothetical in nature and the components are not independently tradable.** However, it helps us shed some light on the key drivers behind the difference in performance between shorter-dated and longer-dated variance swaps

- **The accrued P&L contribution highlights greater premium on offer in longer dated tenors.** The back-tested performance since 2001 exhibits ~1.5x greater premium for 1y var selling vs 1m with only marginally higher volatility. This has resulted in a superior risk-adjusted performance (attributable to accrued P&L) for 1y var.

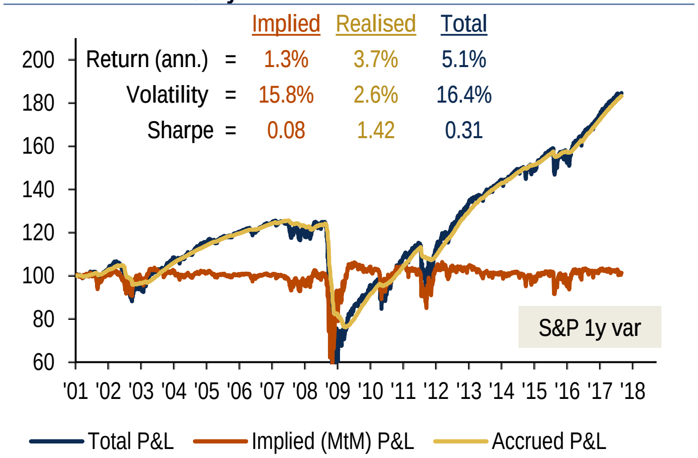
- **However, greater vega sensitivity for 1y var has led to significantly higher volatility and thus lower risk-adjusted performance.** While the average P&L attributed to implied volatility (vega sensitivity) is negligible, the volatility of implied P&L for 1y var was 4.5x higher than 1m var. This additional portfolio volatility diminished the higher risk-adjusted returns of the accrued component, in our back-tests.

Chart 45: For S&P 1m var the risk due to exposure to implied volatility changes is ~0.7x higher than the risk due to realised volatility



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-01 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 46: The risk due to implied vol mushrooms to 6x that of realised vol in the case of S&P 1y var



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-01 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

How do VRP strategies fit into portfolios?

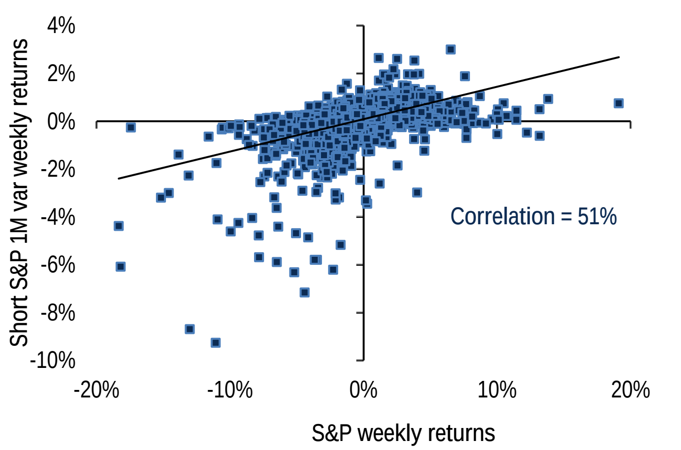
Our back-tests show:

- Equity + 5% VRP improved Sharpe by 0.05 with only 1% tracking error
- X-asset VRP generated 50% higher risk/reward vs. its components
- Adding VRP to a x-asset risk factor portfolio increased Sharpe by 0.4
- Hedging VarSwap 'shadow' delta creates market-neutral VRP exposure

A case for using short var to (partly) replace equities

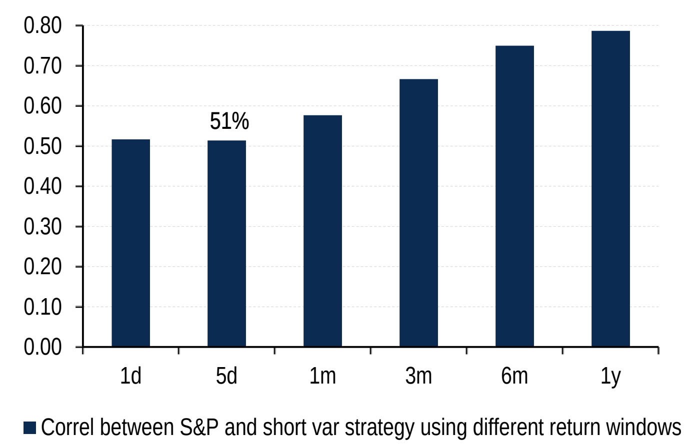
A short vol position is strongly (positively) correlated to long equities (Chart 47), and is implicitly long equity risk. It is interesting to note from Chart 48 that the relationship becomes stronger as the observation window increases. Moreover, short variance strategies have historically generated higher risk-adjusted returns versus being long equities. As a result, several market participants have considered replacing – and some indeed have partly replaced – their long equity exposure with short vol.

Chart 47: The short S&P 1m var strategy performance is strongly (positively) correlated to long equities



Source: BofA Merrill Lynch Global Research. Data from 19-Jan-01 to 22-Aug-17

Chart 48: The correlation between short S&P var and long S&P becomes stronger as the observation window increases

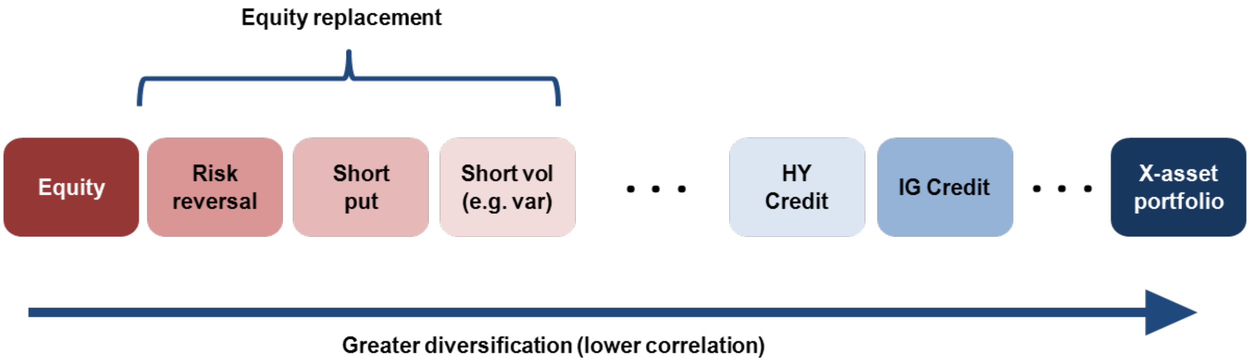


Source: BofA Merrill Lynch Global Research. Data from 19-Jan-01 to 22-Aug-17

Chart 49 illustrates where short vol fits, in our view, within the spectrum of equity replacement vs truly diversified cross-asset portfolios. While risk reversals (and short puts to some extent) are closest in terms of equity replacement alternatives, short volatility falls somewhere between pure equity replacement and being a portfolio diversifier. Indeed, a risk reversal taken to its limit where both put & call strikes are the same is akin to being long equities. On the other hand, the relationship between short vol and long equities is less direct, yet empirically quite robust. As a result, adding short volatility exposure to a long only cross-asset portfolio offers some (but limited) diversification benefits while it adds to equity risk. Therefore, it is more sensible to think of short volatility as equity replacement.

How does short vol exposure differ from being long equities? While a short variance strategy is typically profitable more often than long equities, it can also have sharper drawdowns (albeit with shorter recovery times, Chart 39). The key difference between the two however comes from the short var strategy's likely under-performance in sharp equity rallies as it is not strongly geared to high growth environments like equities are. In fact, the basis between the two is highest in sharp but violent market rallies as seen from the top right quadrant in Chart 47, leading to strong equity performance but relatively lacklustre returns for short variance.

Chart 49: The road to asset diversification starts with replacement



Source: BofA Merrill Lynch Global Research.

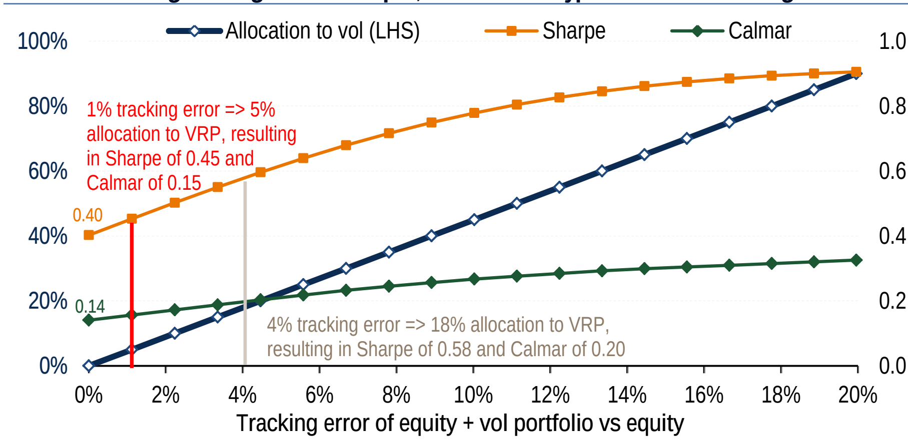
How much of equity to replace with a short equity vol allocation?

The key question that investors face when thinking of replacing long equities with short vol exposure is how much to allocate to the short vol strategy. If long-run theoretical risk-adjusted returns were to be considered as the only criterion, one would replace the entire equity exposure with short vol exposure. However, reality is more nuanced and allocation to short vol depends on the flexibility that an investor's mandate offers in terms of taking on the basis risk as well as capacity constraints in the volatility market.

Finding an acceptable tracking error may help answer the sizing question: In our view, this is a pragmatic and effective method which starts by defining the tracking error that an investor is willing to accept when considering equity replacement. It is also a relatively more familiar question for most portfolio managers versus other approaches one could adopt, such as equalising historical risk (in terms of volatility, drawdowns, upside beta etc.) for short volatility vs long equities. The volatility allocation is then determined such that portfolio tracking error is unlikely to exceed the allowable limit.

An illustration: In Chart 50, we plot the tracking error of an equity + vol portfolio vs equity on the x-axis and risk-adjusted returns on the y-axis for different (short) vol allocations. For instance, an investor willing to accept 1% (4%) tracking error should consider a 5% (18%) allocation to the ratio-sized VRP strategy[5]. Even a 5% allocation would have improved the equity Sharpe by 0.05, based on our hypothetical back-test.

Chart 50: Since 2001, even a 5% short equity var allocation would have improved equity Sharpe by 0.05 while limiting tracking error to 1% p.a., based on our hypothetical back-testing



Source: BofA Merrill Lynch Global Research. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

[5] Note, the (short) vol allocation to in this framework is a function of how the VRP strategy is sized. Here, we use Leverage = 0.2, which gives us a %-vega sizing of 0.2*20/VarStrike.

Adding (short) volatility to x-asset risk factor portfolios

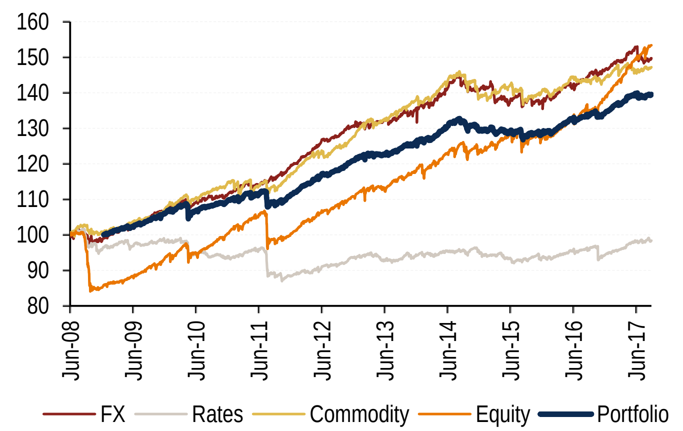
In the Risk 'n mix report, we discussed the pros and cons of different allocation/ optimization techniques with regards to cross-asset risk factor portfolios & highlighted our preference for using (i) Equal risk contribution (ERC)-based sizing methods and (ii) a 2-step allocation process using risk factor clustering. In our view, such an approach offers a solid balance between the stability of weights, concentration risk, historical risk-adjusted returns and diversification of portfolios. Although the entire analysis in the piece was focussed on linear risk factors (carry, momentum & value), we emphasized the need, and proposed techniques, to adapt the allocation methodology to reflect the 'fat-tailed' nature of non-linear risk premia strategies such as short volatility.

Enhanced-ERC: apply tail-aware risk measures on an expanding window of observations: We adapt our ERC-based portfolio allocation method to account for the fat-tailed return distributions of non-linear risk premia strategies (particularly short vol) such that: 1) We use tail volatilities and tail correlations when quantifying 'risk' in ERC, and 2) we use the entire trailing history available at any given point of time, rather than a rolling observation window. The rest of the portfolio construction approach is similar to what we outlined in our Risk 'n mix publication.

Vol ratio-sizing also accounts for different base levels of cross-asset vols: Chart 51 & Table 4 show the back-tested results of a short 1m var selling strategy (vol ratio-sized) across different assets. All strategies with the exception of rates demonstrated robust risk-adjusted back-tested results since Jun08. It is interesting to note that the standard deviation of short var across assets would have been of a similar magnitude. This demonstrates how vol ratio-sizing also allows for a relatively fairer comparison across asset classes by assigning higher vega to low vol assets and vice versa.

FX & Rates (short) var can provide diversification benefits to underlying assets: It is interesting to note that while short vol strategies in Equities (& Commodities to a lesser extent) are significantly positively correlated to their underlying assets, the correlation is near flat for Rates & FX. This is consistent with our observation from Chart 63 (Appendix) that gains in Equity and Commodity vol are greater for downside returns while Rates and FX show a more balanced picture (i.e. vol can rise for moves in either direction). Hence, the case for replacing the underlying asset with short volatility is strongest for equities. Conversely, adding Rates and FX (short) vol exposure to their underlying assets can provide diversification benefits.

Chart 51: Hypothetical back-tested short 1m variance swap (ratio-sized) strategies across asset classes & enhanced-ERC based short vol portfolio



Source: BofA Merrill Lynch Global Research. Data from 20-Jun-08 to 15-Sep-17. We use FXE (EURUSD), TLT (US rates), USO (Oil) & S&P as proxies for FX, Rates, Commodity and Equity. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Table 4: A cross-asset short 1m var portfolio exhibited ~50% superior risk-adjusted returns vs its components, in our back-test

Strategy	Return	Volatility	Sharpe	MaxDD*	Calmar	Correl**
FX	4.8%	3.8%	1.28	-6.5%	0.74	9%
Rates	0.3%	3.7%	0.08	-12.3%	0.02	-7%
Commodity	4.4%	3.8%	1.16	-6.5%	0.68	23%
Equity	6.8%	5.3%	1.28	-10.0%	0.68	57%
X-asset avg.	3.9%	4.0%	0.98	-8.4%	0.46	
Vol Cluster	3.9%	2.8%	1.41	-4.6%	0.85	

Source: BofA Merrill Lynch Global Research. Data from 20-Jun-08 to 15-Sep-17. We use FXE (EURUSD), TLT (US rates), USO (Oil) & S&P as proxies for FX, Rates, Commodity and Equity *MaxDD = Max Drawdown. ** Correlation vs their underlying assets. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

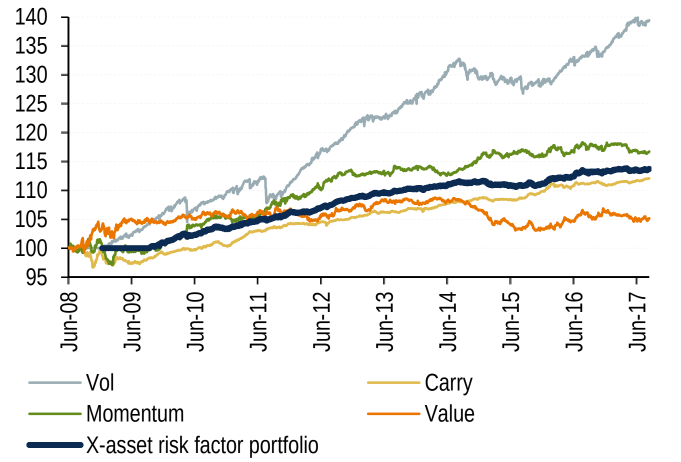
Vol cluster exhibited ~50% superior risk-adjusted returns vs its components

Finally, when comparing the back-tested results of the short Volatility cluster vis-à-vis average returns across asset classes, we note a significant (~30%) reduction in standard deviation with no material change in return. This led to a superior Sharpe ratio for the portfolio. At the same time, the Calmar ratio of the cluster was ~2x the x-asset average.

Adding short vol to a x-asset linear risk factor portfolio improved Sharpe by 0.4

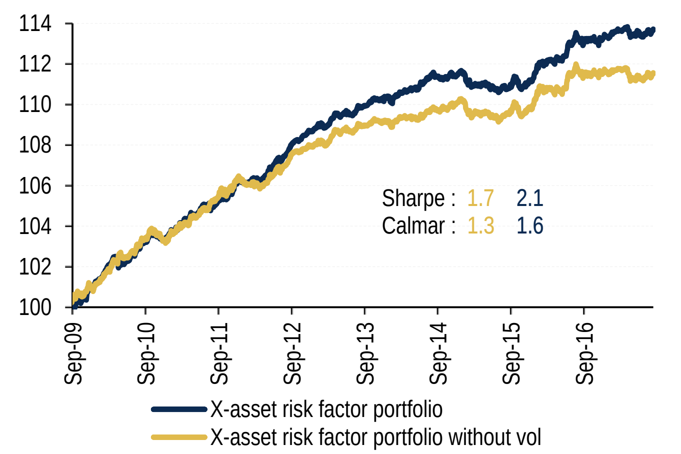
Chart 52, Chart 53 and Table 5 highlight the benefit of adding volatility as a factor to traditional linear risk factors such as Carry, Momentum and Value (as defined in our Risk 'n mix report). The Sharpe ratio of the X-asset risk factor portfolio based on Carry, Momentum & Value improves from 1.7 to 2.1 on adding Volatility as a factor. This is largely on account of increased returns as volatility of the portfolio remains broadly unchanged. Interestingly, adding short volatility also led to reduced drawdown in the portfolio. Indeed, short vol factor has been negatively correlated (albeit weakly) to our Carry, Momentum & Value factor implementations.

Chart 52: Hypothetical back-tested performance of a cross-asset risk factor portfolio



Source: BofA Merrill Lynch Global Research. Data from 20-Jun-08 to 31-Aug-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 53: Impact of adding short vol exposure to cross-asset (linear) risk factor portfolio



Source: BofA Merrill Lynch Global Research. Data from 20-Jun-08 to 31-Aug-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Table 5: Adding short vol exposure to a x-asset risk factor portfolio would have increased portfolio Sharpe by 0.4, primarily due to higher back-tested returns

Strategy	Return	Vol	Sharpe	MaxDD*	Calmar
Vol	3.8%	2.8%	1.3	-4.6%	0.8
Carry	1.7%	0.8%	2.1	-0.9%	2.0
Momentum (Mom)	2.0%	1.9%	1.1	-1.7%	1.2
Value	0.1%	1.8%	0.0	-5.3%	0.0
Carry + Mom + Value	1.3%	0.8%	1.7	-1.1%	1.3
Carry + Mom + Value + Vol	1.6%	0.8%	2.1	-1.0%	1.6

Source: BofA Merrill Lynch Global Research. Data from 20-Jun-08 to 31-Aug-17. * MaxDD = Max DrawDown. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Table 6: Interestingly, the (short) vol factor has been negatively correlated (albeit weakly) to simple Carry, Momentum & Value factor implementations since 2008

	Vol	Carry	Momentum	Value
Vol	-	-3%	-9%	-3%
Carry	-3%	-	16%	19%
Momentum	-9%	16%	-	-19%
Value	-3%	19%	-19%	-

Source: BofA Merrill Lynch Global Research. Data from 20-Jun-08 to 31-Aug-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

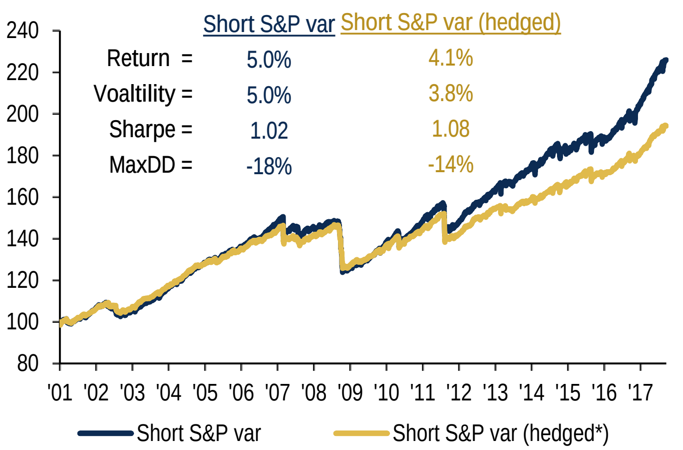
Hedge VarSwap 'shadow' delta for a market neutral exposure to equity var

It should be noted that the Volatility factor adds potential beta exposure to a cross-asset (long-short) risk factor portfolio owing to the positive correlation between equities and short var (note: this dependence is not as elevated for other asset classes, see Table 4). This is in stark contrast to market-neutral implementations that we outlined for Carry, Momentum and Value in our Risk 'n mix report. For investors who want to maintain close to market-neutral exposure in their short vol implementations, we suggest hedging the 'implicit' delta of the variance swap to the underlying asset.

A crude approximation: delta-hedge using a linear skew estimate for VarStrike

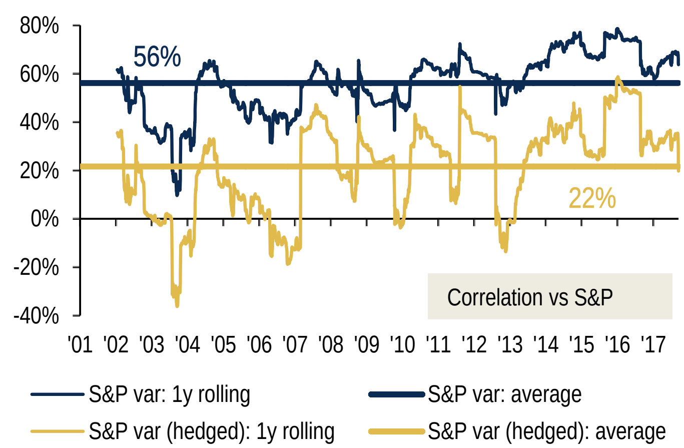
To illustrate the potential benefit of hedging variance swap delta, we use the well-known linear skew approximation[6] for the variance strike to determine our delta hedge at any given time. We find that delta hedging, even under this crude assumption, reduces the correlation to equities of a short variance strategy from 56% to 22% (on average). Moreover, the back-tested results of the (delta) hedged strategy was comparable (in fact slightly superior) to that of unhedged short var. This, in our view, illustrates the robustness of volatility risk premium (Chart 54 and Chart 55).

Chart 54: Delta hedging, even under the linear skew assumption, illustrates the robustness of volatility risk premium...



Source: BofA Merrill Lynch Global Research. Data from 19-Jan-01 to 15-Sep-17. * Hedging the VarSwap delta using linear skew approximation for variance strike. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 55: ... as well as reduces the correlation of short variance strategy vs S&P from 56% to 22% (on average, since 2001)



Source: BofA Merrill Lynch Global Research. Data from 19-Jan-01 to 15-Sep-17. * Hedging the VarSwap delta using linear skew approximation for variance strike. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

[6] Under linear skew approximation, VarSwap strike is given by $K = \sigma_{ATM} \times [1 + (3 \times T \times Skew^2)]$

Selling vol in low vol regimes

- Historically, short vol offered better risk/reward in low vol regimes
- Short vol had longer periods of consecutive gains in low vol regimes
- Realised vol typically transitions from low to high levels gradually
- Sharp, short-lived vol spikes pose MtM risk but may not lead to losses

The long term first quartile level of the VIX (since 1990) is just under 14 vols. In recent years however (since 2014), the VIX has been trading below 14 more frequently than not. It therefore seems fair to characterise the current environment as a low volatility regime, akin to the '92-'95 and '04-'06 periods. This is not to say that volatility has not spiked on occasion but rather that any such spike has been relatively short-lived. In fact, the high intensity and short duration of vol spikes have been particularly stark during '14-'17 vs. previous low vol periods – a phenomenon we have termed fragility and discussed extensively over the past few years. Surely, the question on many investors' minds is whether the current low vol environment is conducive to short vol strategies or fraught with risks as there is – at least in principle – more room for vol to trade higher.

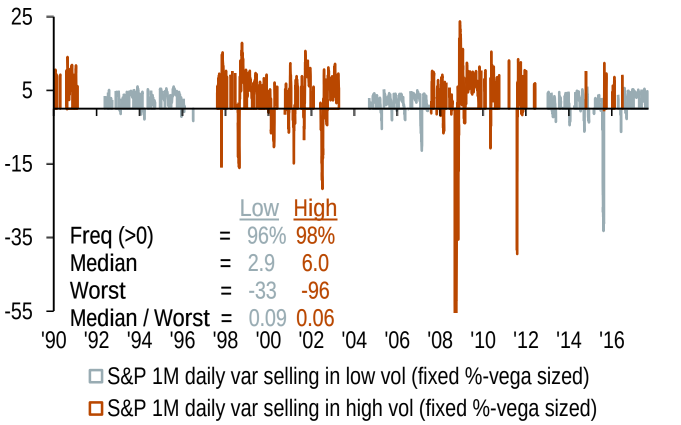
In our view there are 3 key reasons why a low vol level (alone) should not be viewed as a prohibitive signal for selling vol when viewed from a systematic strategy perspective:

- **Realised volatility does not tend to jump from a low vol to a high vol** regime without spending some time in a transition period (due to the presence of vol auto-correlation, Chart 61). Notably, while the most recent low vol environment has been witness to such quick low to high vol transitions, the fact remains that they have been remarkably short-lived. This suggests that they tend to pose more of a mark-to-market risk as opposed to crystallising sustained losses.

- **Historically, selling vol in low vol regimes has a superior risk-reward profile** when sized appropriately. As we have argued in previous sections, volatility changes are better behaved when viewed as % returns than vol point changes and ratio-sizing a short vol position yields a more consistent risk-reward profile over varying volatility regimes. Indeed, as Chart 57 and Chart 59 show, a ratio-sized short vol trade would have exhibited a greater propensity for higher gains as well as more limited losses during low vol periods. Note that the same assertion is harder to make when sizing for fixed % vega (Chart 56 and Chart 58)

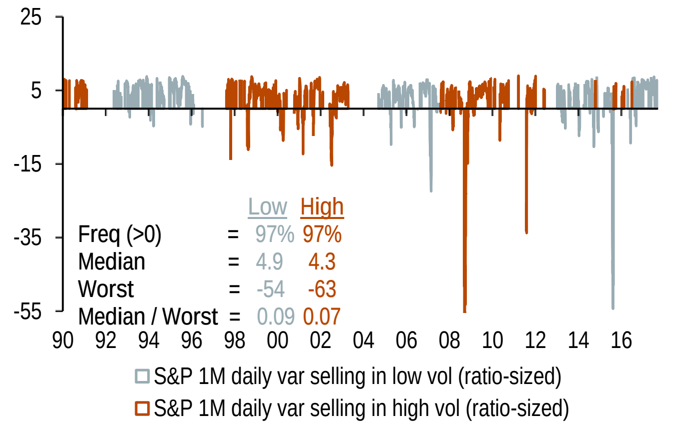
- **Option prices often embed a healthy risk premium** when equities are in a range and vols are trapped near a perceived floor. Indeed, Chart 60 shows that (daily) vol selling has exhibited longer periods of consecutive gains in low vs. high volatility environments. In fact, the latest such 'winning streak' (from 21-Sep-16 to 4-Aug-17) was the 4th largest (within high or low vol regimes) since 1990.

Chart 56: When sized for fixed % vega, short var gains as well as losses are amplified in high volatility regimes



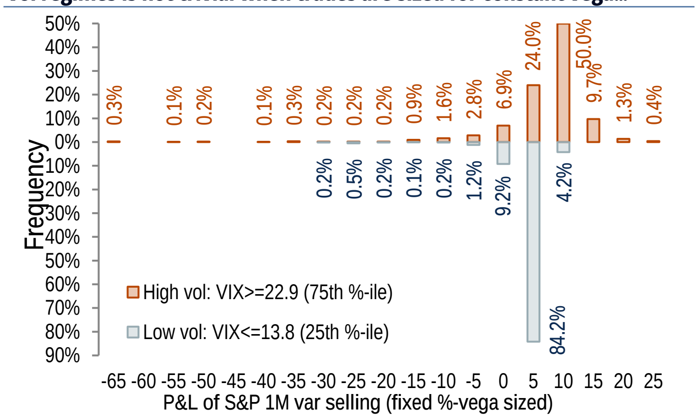
Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 57: When ratio-sized, short var gains are equally probable in low and high vol regimes but the risk-reward profile is superior for low vol



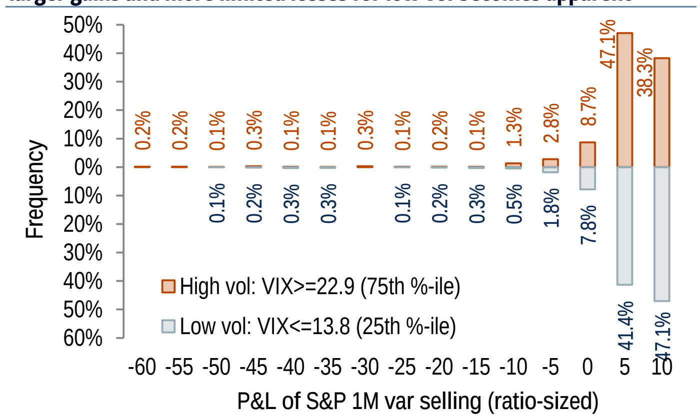
Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 58: Comparing the P&L profiles for var selling during high vs. low vol regimes is not trivial when trades are sized for constant vega...



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

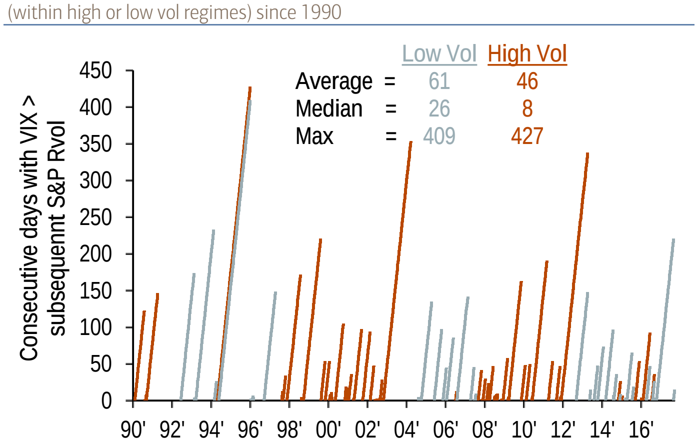
Chart 59: ... but becomes easier when ratio-sized: the propensity for larger gains and more limited losses for low vol becomes apparent



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 60: Option prices often embed a healthy risk premium when equities are in a range and vols are trapped near a perceived floor

The latest such 'winning streak' (from 21-Sep-16 to 4-Aug-17) was the 4th largest (within high or low vol regimes) since 1990



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 15-Sep-17.

Chart 61: RV does not tend to suddenly jump from low to high vol regimes (& vice versa): e.g., RV ended below median levels 94% of the time when RV was in its 10th decile in the prior month

Numbers denote the percentage of times RV ended up in a given decile after 1m given the starting decile of RV

Starting percentile of S&P 1M RV (columns); Percentile of S&P 1M RV after 1M (rows)

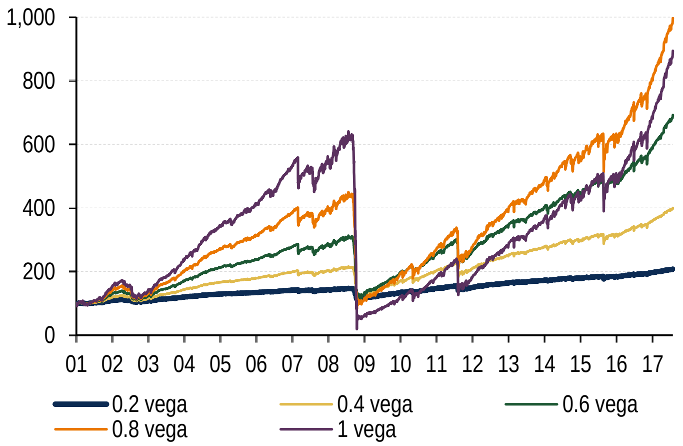
	0 to 10	10 to 20	20 to 30	30 to 40	40 to 50	50 to 60	60 to 70	70 to 80	80 to 90	90 to 100
0 to 10	46%	21%	14%	9%	4%	2%	2%	2%	0%	0%
10 to 20	21%	21%	18%	17%	8%	6%	5%	3%	1%	0%
20 to 30	12%	21%	18%	15%	12%	10%	6%	4%	1%	1%
30 to 40	9%	14%	15%	16%	17%	12%	10%	4%	2%	1%
40 to 50	5%	9%	11%	13%	17%	15%	15%	8%	5%	1%
50 to 60	2%	6%	11%	13%	14%	18%	15%	12%	8%	2%
60 to 70	2%	4%	7%	8%	13%	16%	16%	20%	10%	4%
70 to 80	1%	3%	4%	5%	8%	11%	15%	22%	23%	8%
80 to 90	0%	1%	1%	3%	5%	8%	10%	17%	34%	20%
90 to 100	0%	1%	1%	2%	2%	2%	5%	8%	16%	64%

Source: BofA Merrill Lynch Global Research. Data: 2-Jan-28 to 27-Sep-17.

Appendix

In this section, we provide cross-asset illustrations of some of the key observations pertaining to equities earlier in the report.

Chart 62: Leverage is a key consideration in allocating to short var – shown here for fixed %-vega sizing



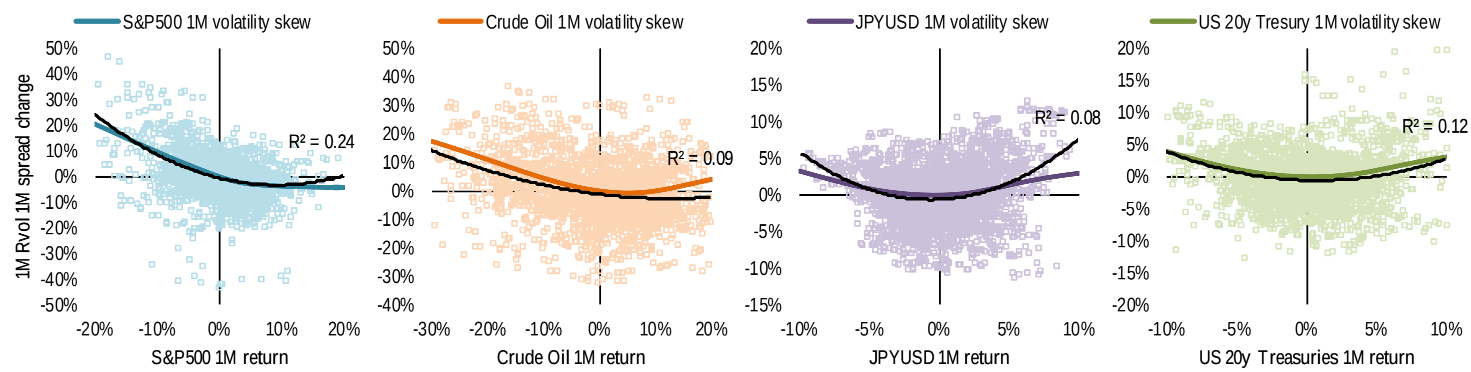
Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 25-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Table 7: Higher leverage to short var increases Calmar ratios but at the expense of longer recovery times. Daily Sharpe reduces considerably more than in the ratio-sized strategy

Vega per $100 →	0.2	0.4	0.6	0.8	1	S&P
Ann return	4.6%	9.0%	13.3%	17.4%	26.5%	6.0%
Stdev	5.2%	10.7%	16.8%	24.6%	45.0%	19.2%
Sharpe (daily)	0.89	0.85	0.79	0.71	0.59	0.31
Sharpe (monthly)*	0.79	0.79	0.79	0.79	0.79	0.32
Max Drawdown	-24%	-45%	-64%	-82%	-97%	-57%
Calmar	0.19	0.20	0.21	0.21	0.27	0.10
Recovery time (yrs)	2.5	2.8	3.9	5.1	8.3	6.1

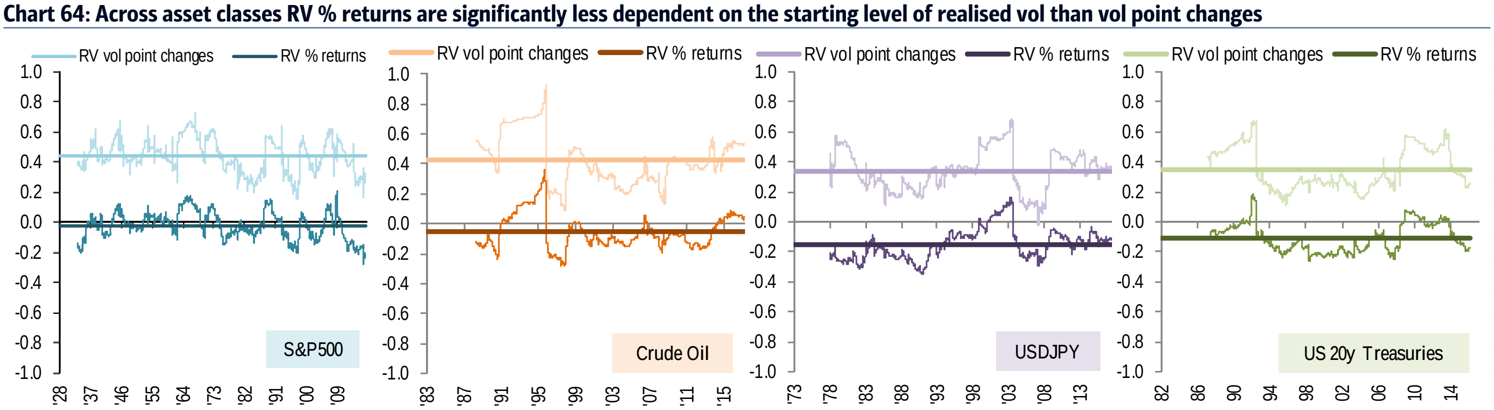
Source: BofA Merrill Lynch Global Research. Data: 2-Jan-90 to 25-Sep-17. *On rebalance dates. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 63: Implied volatility skew generally mirrors the broad relationship between X-asset returns and changes in realised volatility



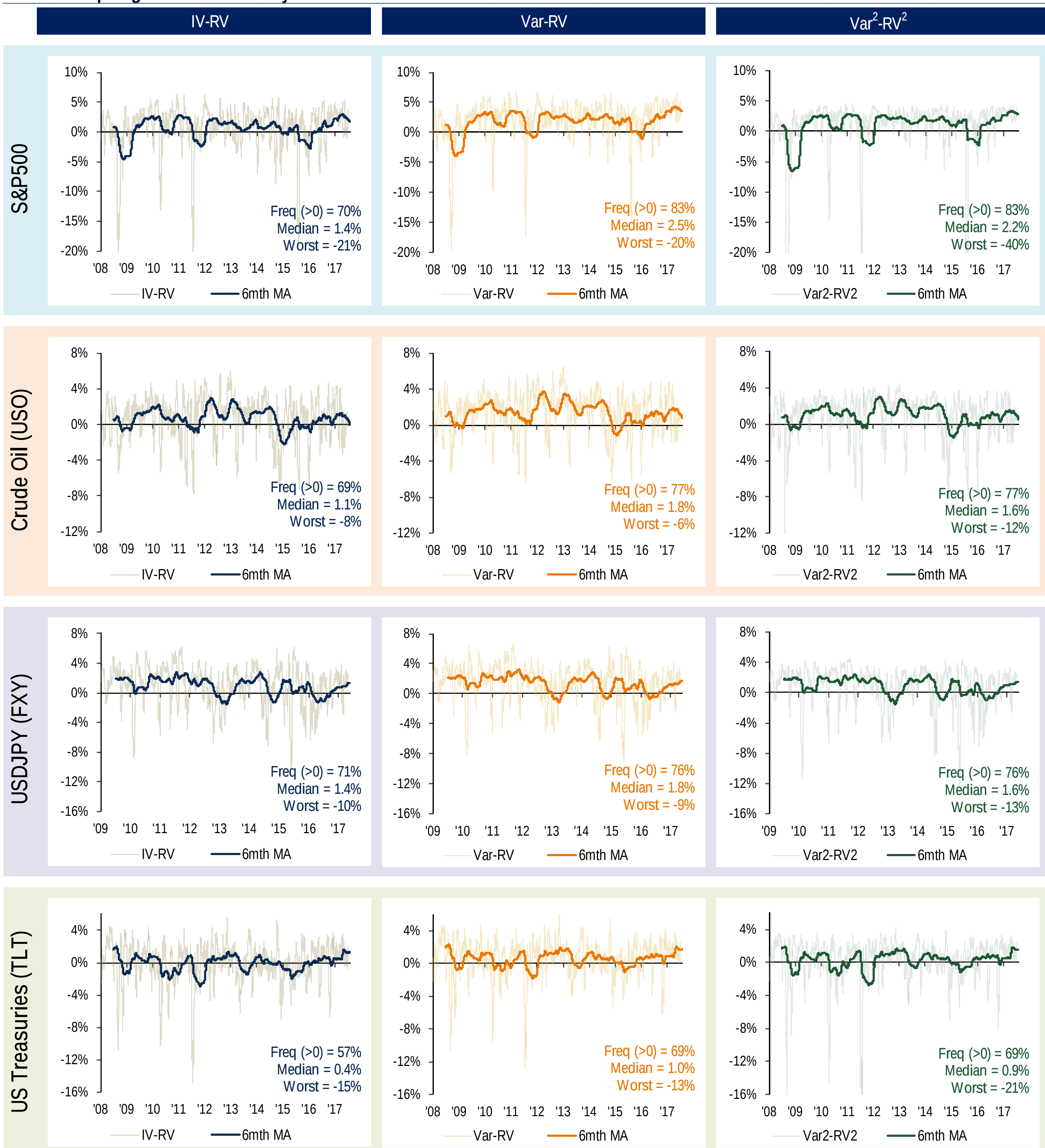
Source: BofA Merrill Lynch Global Research. Data: 3-Jan-00 to 23-Aug-17 for S&P and JPYUSD (FXY), 26-Jul-02 to 23-Aug-17 for US Treasuries (TLT) and 10-Apr-06 to 23-Aug-17 for Crude Oil (USO). Skew is an average of historical skew levels since May-09.

Chart 64: Across asset classes RV % returns are significantly less dependent on the starting level of realised vol than vol point changes



Source: BofA Merrill Lynch Global Research. Data: 3-Jan-1928 to 27-Apr-2017 for S&P, 3-Jan-1928 to 4-Apr-1983 for Crude Oil, 2-Jan-1973 to 27-Apr-2017 for USDJPY and 5-May-1982 to 27-Apr-2017 for US Treasuries.

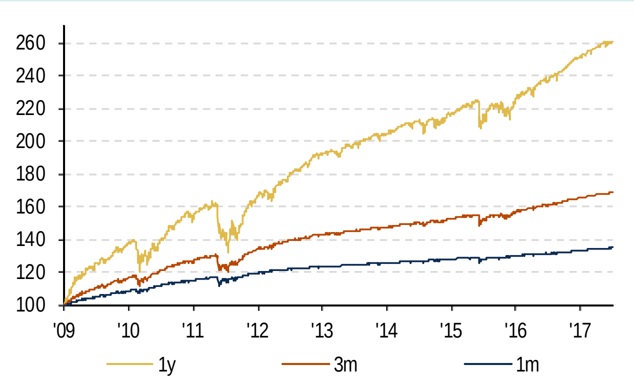
Chart 65: Comparing measures of Volatility Risk Premium across asset classes



Source: BofA Merrill Lynch Global Research. Data: 2-Jan-08 to 2-Aug-17 (10-Mar-09 to 2Aug-17 for USDJPY). Sized by 1/(2 x Var) for easier comparison with IV-RV and Var-RV

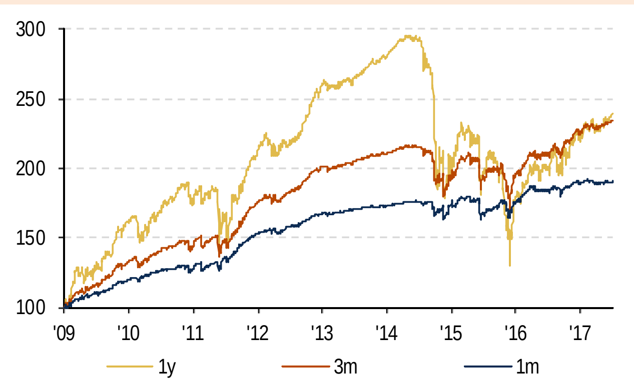
Chart 66: Short var selling for different tenors across asset classes: shorter-dated tenors tend to offer better value than longer-dated ones

S&P500



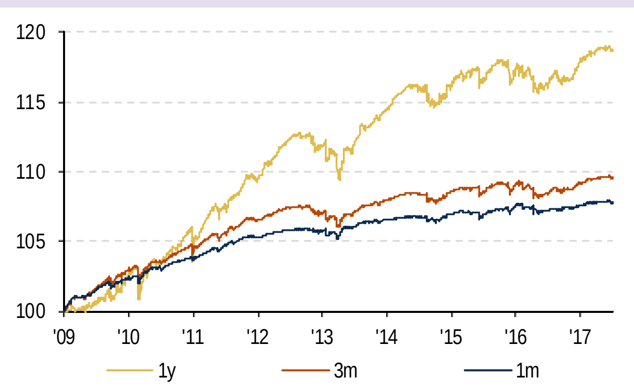
Statistics	1m	3m	1y
Ann. return	3.6%	6.3%	11.8%
Volatility	2.6%	4.4%	9.5%
Sharpe	1.36	1.43	1.24
Max Drawdown	-4.6%	-7.5%	-19.2%
Calmar	0.78	0.83	0.61
Recovery time (yrs)	0.4	0.5	0.6

Crude Oil (USO)



Statistics	1m	3m	1y
Ann. return	7.8%	10.5%	12.3%
Volatility	6.1%	9.3%	19.8%
Sharpe	1.28	1.13	0.62
Max Drawdown	-9.6%	-21.5%	-55.9%
Calmar	0.81	0.49	0.22
Recovery time (yrs)	0.8	2.1	3.1

USDJPY (FXY)



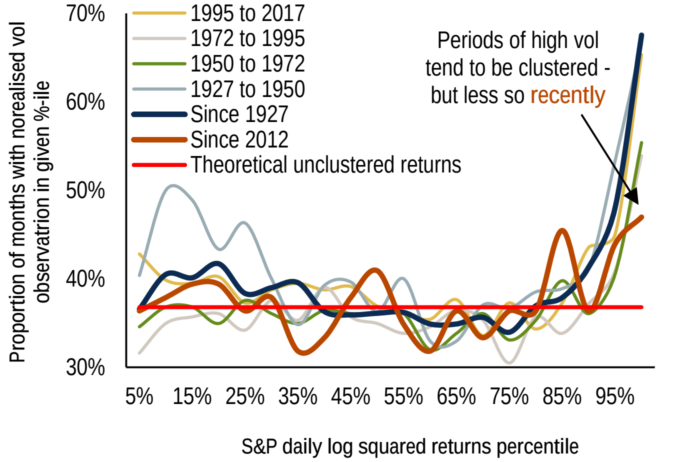
Statistics	1m	3m	1y
Ann. return	0.9%	1.1%	2.0%
Volatility	0.7%	0.9%	2.0%
Sharpe	1.37	1.15	1.03
Max Drawdown	-0.8%	-1.5%	-3.1%
Calmar	1.17	0.74	0.66
Recovery time (yrs)	1.0	1.1	1.2

Treasuries (TLT)

Statistics	1m	3m	1y
Ann. return	0.4%	0.9%	3.4%
Volatility	1.1%	1.6%	5.7%
Sharpe	0.34	0.59	0.59
Max Drawdown	-3.1%	-5.1%	-8.9%
Calmar	0.12	0.18	0.38
Recovery time (yrs)	1.5	1.5	1.4

Source: BofA Merrill Lynch Global Research. Data: 20-Mar-09 to 15-Sep-17. Back-tested performance is hypothetical in nature; it is not intended to be an indicative of actual or future performance. The actual performance of strategies may vary significantly from back-tested performance

Chart 67: Clustering of daily returns is evident across multiple time-frames although it has been weaker more recently



Source: BofA Merrill Lynch Global Research. Data: Dec-1927 to Apr-17. *Assuming daily returns are independently and identically distributed, it can be shown that the expected number of months which contain no observation belonging to a given set of observations of size P (e.g., the 0th to 5th percentile bucket) is given by $(1-1/M)^P$, where M is the total number of months. If P is roughly equal to M (as is the case here since 21 days x M = total number of observations = 20 x P) and M is large enough, this can be approximated by exp(-1), which is the red line in the chart.

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