VIX Futures ETNs: Tracking Efficiency, Consistency and Price Discovery

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We examine the tracking efficiency, price consistency and price discovery in the the VIX futures Exchange Traded Note (ETN) market, which has been well-developed since 2009. We provide evidence that VIX futures ETNs are not efficiently tracking their indicative values. We also find that VIX futures ETN prices are mostly priced consistently, that is, they have consistent implied index performance factors. We find that the ETN prices predominantly Granger cause futures prices at the intraday level, although the relationship is time varying, therefore the ETNs lead the futures in price discovery. This could explain the contemporaneous tracking inefficiency of the ETNs. Price discovery among the different ETNs seems to happen fairly contemporaneously, although these relationships are also time varying. This is in line with the ETNs being priced consistently.

Keywords: VIX futures ETNs; Tracking; Market Dynamics; Consistency; Price Discovery

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1 Introduction

In this paper we examine the tracking efficiency, consistency and price discovery in the young but rapidly growing VIX futures Exchange Traded Note (ETN) market, at both the daily and intraday level[1]. We provide evidence that VIX futures ETNs are not efficiently tracking their indicative values, contemporaneously. This is consistent with the strong one way Granger causality we find from VIX futures ETNs to VIX futures. We find that the ETN prices predominantly lead the futures prices at the intraday level, showing that price discovery happens in the ETN market first. Combining our results with previous research on the price discovery of the VIX index and its derivatives (Shu and Zhang (2012), Frijns, Tourani-Rad, and Webb (2015) and Bordonado, Molnár, and Samdal (2016)) we could conjecture that price discovery happens first in the VIX futures ETN market, followed by the VIX futures Exchange Traded Fund (ETF) market, then the VIX futures market and finally shows up in the VIX index. We also investigate the consistency of the ETN prices and find that they are mostly consistent at the daily level. When we investigate the Granger causality between different ETNs we find significant two-way Granger causality, price discovery happens simultaneously in the ETNs supporting our finding that they are priced consistently, however these price discovery relationships are time varying.

The Chicago Board Options Exchange (CBOE) Volatility index (VIX) was first introduced in 1993 and has rapidly become the benchmark for investor sentiment[2]. However the VIX index is not trade-able directly and replication through the numer-

[1] An Exchange Traded Note (ETN) is non-securitized debt obligation, like a zero coupon bond, that has a final redemption value based on the value of some underlying benchmark

[2] The methodology of the VIX index was changed in 2003. It was originally calculated based on the implied volatilities of at-the-money S&P 100 index options (Whaley, 1993), it now reflects the implied volatility of S&P 500 index options.

ous S&P 500 options, although possible, would be impractical and costly. On the 26^{th} of March 2004 CBOE launched VIX futures contracts, that were soon followed by the birth of VIX options in 2006 and VIX futures indices in early 2009. The two most followed VIX futures indices are the S&P 500 VIX futures Short-Term index (SPVXSTR) and its Mid-term sibling (SPVXMTR). The short-term (mid-term) index tracks the performance of a daily rebalanced VIX futures position in the nearest and second nearest (4^{th}, 5^{th}, 6^{th} and 7^{th} nearest) maturing futures to achieve an almost constant one (5) month maturity. Gehricke and Zhang (2015) show that the weighted average maturity of the underlying futures position of the short-term index fluctuates around 30 days and is not constant. The indices come in Total-Return and Excess-Return versions, where the Total-Return is equal to the Excess-Return index with an added risk free return earned on the hypothetical notional value for the underlying VIX futures position.

On the 29^{th} of January, 2009, the first Exchange Traded Products (ETPs) on VIX futures indices, the VXX and VXZ ETNs, were issued by Barclays Capital iPath. The introduction of these products has led to a large increase in the trading of VIX futures and has altered their market micro-structure (Fernandez-Perez, Frijns, Tourani-Rad, and Webb (2015) and Bollen, O'Neill, and Whaley (2016)). There are now many more of these products with different specifications of their underlying indicative values. Exchange Traded Funds (ETFs) on VIX futures indices have also been introduced recently.

Table 1 provides a summary of the VIX futures ETNs we study in this paper. The total market cap for the VIX futures ETN market, as of 31^{st} of March, 2016, is \$US 2.6 Billion and it has a total average daily dollar trading volume of \$US 1.6

Billion, making it a substantially large and active market, especially for its young age. In figure 1 we show the 10-day moving average of total daily dollar trading volume and total daily capitalization of the VIX futures ETN market. We can see that although market capitalization has stayed fairly stable since 2010 the dollar trading volume has steadily grown since 2010 and often spikes, sometimes as high as twice the market capitalization. In table 1 we report the abysmal performance of long exposure ETNs and the positive performance of inversely levered ETNs over our sample, which is in line with the findings in the literature (Whaley (2013), Eraker and Wu (2013), Bordonado, Molnár, and Samdal (2016), among others). As most of the ETNs issued are long exposure, the issuers of the ETNs stand to make potentially large profits through these ETNs. Table 2 shows an approximate of the maximum profit the different issuing institutions could have made if they did not hedge their ETN exposure outside of their inverse exposure ETNs. From the table we can see that Barclays, Credit Suisse, UBS and Citi Bank have a potential un-hedged profit of $US 6.31 Billion, $US 1.17 Billion, $US -8.07 Million and $US 658.30 Million, respectively.

The rest of the paper is organized as follows, in the next section we will review several important strands of literature related to this paper, followed by a description of the data we use in this study, in section 3. Then in section 4 we study the tracking efficiency of VIX futures ETN prices. Section 5 presents the analysis of the consistency of the different ETN market prices. In section 6 we explore the price discovery relationship between the VIX futures ETNs and VIX futures and between the different VIX futures ETN pairs. Lastly in section 7 we offer our conclusions and discussions.

2 Literature

Several branches of Literature have evolved around the VIX index and its derivatives in recent years. One example is, due to the negative correlation between the VIX and S&P 500 index, the usefulness of VIX derivatives as hedging or diversification tools (see: Daigler and Rossi (2006), Szado (2009), Chen, Chung, and Ho (2011) Alexander and Korovilas (2012), Hancock (2013) Bordonado, Molnár, and Samdal (2016), among others). Another very popular branch is that of modeling the VIX and its derivatives. VIX futures price modeling has been done extensively and ever more precisely in recent studies (see: Zhang and Zhu (2006), Zhang, Shu, and Brenner (2010), among others). Mencía and Sentana (2013) empirically test the performance of several models for pricing VIX derivatives. Gehricke and Zhang (2015) model the VXX in a Heston (1993) framework and show that the negative returns of the VXX ETN are due to the roll yield of the underlying futures position. The roll yield is predominantly negative in normal times due to the contango term structure of VIX futures which is driven by the normally negative market price of variance risk.

Some literature has developed around the price discovery dynamics of the VIX index and its futures. Shu and Zhang (2012) employ linear and non-linear causality tests to investigate the relationship of the VIX index and its futures prices, at the daily level. They conclude that there is a two-way Granger causality relationship between the VIX and its futures, suggesting that price discovery happens simultaneously. Frijns, Tourani-Rad, and Webb (2015) also investigate the relationship between the VIX index and its futures prices at the daily and intraday level. At the daily level their results are consistent with Shu and Zhang (2012). However, at the intraday level Frijns, Tourani-Rad, and Webb (2015) find strong evidence for a one way Granger causality from the VIX futures to the VIX index, suggesting that price discovery happens first in the futures market. They also investigate what drives the dominance of VIX futures and find that the leading relationship is stronger on days with negative returns to the S&P 500 index and on days with high values of VIX. We add to these findings by showing that VIX futures ETNs actually lead VIX futures. Then combining our results with those of Frijns, Tourani-Rad, and Webb (2015), the logical conclusion is that the price discovery happens first in VIX futures ETNs then VIX futures and then the VIX index.

Alexander and Korovilas (2013) show that the large scale hedging by the ETN issuers is likely to influence the level and volatility of VIX futures prices. They showed that speculators could be front running this hedging, although the front running profits have decreased over time. While Simon (2016) demonstrates some VIX options trading strategies to take advantage of the term structure of VIX futures. Mixon and Onur (2015) use unique regulatory data which allows them to identify the actual quantities, rather than a hedging estimate as in Alexander and Korovilas (2013), of futures traded by asset managers and leveraged funds. They find that although the hedging demand from asset managers does impact VIX futures prices so does the offsetting short demand from leveraged funds, who are willing to receive the variance risk premium. Fernandez-Perez, Frijns, Tourani-Rad, and Webb (2015) investigate VIX futures price dynamics in the period before the introduction of VIX futures ETNs and the period after. They find that VIX futures trades have become significantly less informative after the introduction of VIX futures ETNs. Fernandez-Perez, Frijns, Tourani-Rad, and Webb (2015) also give evidence showing that VIX futures ETP hedging demand is influencing VIX futures prices. Bollen, O'Neill, and Whaley (2016) show that the VXX leads the VIX futures in price discovery, which we confirm, but does not consider any other ETNs. They state that this relationship is short lived over 6 seconds or so, however we find the same relationship using high frequency data sampled at 15-second intervals, and for all of the ETNs. Bollen, O'Neill, and Whaley (2016) also show that the VIX futures lead VIX options in price discovery.

Bordonado, Molnár, and Samdal (2016) study the price discovery between three pairs of most traded VIX futures ETFs and ETNs, for non-leveraged and leveraged types. They find that for two of the three pairs the price discovery of ETNs leads the ETFs. For the third pair they find the price discovery is more prominent in the ETF, but the ETN in this pair was the TVIX which we show has behaved very differently to the other ETNs since its issuance halt event. This event has caused our results to differ to those for the rest of the ETNs whenever the TVIX ETN is considered. Their results for the two pairs not including the TVIX are important to our study as they show that the ETNs are leading the ETFs. This dominance of ETNs is likely due to more trading activity and larger market size (Bordonado, Molnár, and Samdal (2016)). In this paper we show that the ETNs lead VIX futures in price discovery, combining this with the results of Bordonado, Molnár, and Samdal (2016), we conjecture that the ETNs lead the VIX futures and the VIX futures ETFs. Further research into the price discovery between VIX futures ETNs and the ETFs may be interesting to complete the picture, as Bordonado et al. (2016) only address this questions indirectly and for three ETN ETF pairs, one of which includes the problematic TVIX ETN. Bordonado, Molnár, and Samdal (2016) also study some hedging and trading strategies using VIX futures ETPs.

Frijns, Gafiatullina, Tourani-Rad, and Fernandez-Perez (2016) study the price discovery between the VXX and XIV ETNs, and what drives the time variation in the relationship. They find that the price discovery of the VXX (relative to the XIV) increases with greater institutional ownership and on those days where the level of the VIX is high. In this paper we also study the price discovery relationships of several VIX futures ETN pairs. We confirm that the relationship between the VXX and XIV, as well as other ETN pairs, is time varying, although most seem to be priced fairly contemporaneously.

Another relevant branch of literature has started to investigate the premium, of a general sample of ETNs, on market prices relative to their indicative values. Wright, Diavatopoulos, and Felton (2010), Diavatopoulos, Felton, and Wright (2011) and Diavatopoulos, Geman, Thukral, and Wright (2014) study the Efficiency Premium in a general sample of ETNs using daily data (not including any VIX futures ETNs). They also investigate some trading strategies for weekly and daily rebalanced portfolios, using the efficiency premium as the trading signal.

3 Data

In this study we use both daily and intraday data for VIX futures ETNs and their indicative values. We do not include those ETNs which have been fully recalled or become stale due to the specification of their indicative methodologies. We exclude these ETNs because understanding their dynamics is no longer of relevant importance and the survivorship bias does not play a role in our paper.

All daily data are obtained from the Bloomberg Professional service. The one second interval intraday quote and 15-second interval intraday indicative value data is taken from the Thomson and Reuters Tick History (TRTH), via SIRCA. Our sample is from the 20th of December 2010 until the 31st of March 2016. However some ETNs inception is after the start date so they are included from their inception date on. There are also some limitations to the data availability for the intraday indicative values of some of the ETNs so they will have shorter sample sizes [3].

When we study the daily tracking efficiency premium, we use closing prices and indicative values. We also study the intraday efficiency premium and the intraday price discovery relationship between the VIX futures and the VIX futures ETNs. For these analyses we sample the mid-quote price at the same 15 second intervals at which the indicative values are reported. We also remove any days where the Chicago futures exchange (CFE) was closed or closed early, as the intraday indicative value is stale on those days.

When we study the price discovery relationships between the ETN pairs we use the 1-second interval sampled intraday mid-quote data. For this analysis we do not need to sample the one second data at a 15 second frequency as all of the ETNs quotes have this higher frequency available (unlike the indicative values). We do not need to remove data for CFE holidays for this analysis as we do not use indicative value data.

4 Tracking efficiency

In this section we study the efficiency of the VIX futures ETNs to track their indicative values. The indicative value represents the value an investor of the ETN would receive at maturity or if they could redeem the ETN instantly. Therefore if the ETNs are priced efficiently we would expect them to track their indicative values

[3] Specifically the intraday indicative value data for the Credit Suisse issued ETNs is only available continuously until mid 2014, after which the data changes format and has many problems.

very closely. The indicative values of the different VIX futures ETNs have slightly different methodologies, but are all based on either the S&P 500 VIX futures Short-Term Total Return index (SPVXSTR), the S&P 500 VIX futures Mid-Term Total Return index (SPVXSTR), or the excess return versions (SPVXSER and SPVXMER respectively)[4].

4.1 Daily efficiency

We first study the tracking efficiency of the VIX futures ETNs at the daily level using daily close prices and closing indicative values. To study the tracking efficiency of the ETNs we first define the efficiency premium as:

$$EP_t = \frac{MV_t - IV_t}{IV_t}, \tag{1}$$

where EP_t is the efficiency premium on day t, MV_t is the closing market value (last price) of the ETN on day t and IV_t is the closing Indicative value of the ETN on day t. Wright, Diavatopoulos, and Felton (2010), Diavatopoulos, Felton, and Wright (2011) and Diavatopoulos, Geman, Thukral, and Wright (2014) investigate a premium in this way to study a sample of general stock market ETNs.

Table 3 shows the average daily efficiency premium (EP_t), its standard deviation and confidence interval, for each ETN. The average of the daily efficiency premium is significant at traditional levels for a majority of the ETNs. Although the VXX, XIV, VIIX and VIIZ ETNs do not have statistically significant mean daily efficiency premiums. The VXX and XIV are the most traded ETNs by far and therefore it could be expected that they are priced more efficiently. Why the VIIX and VIIZ are also

[4]We have summarized the indicative value methodologies for each of the ETNs in the Appendix section A.1.

priced efficiently, at the daily level, cannot be explained by trading volume as their average daily trading volumes are only 89,400 and 5,700 shares a day, respectively.

The TVIX has the third highest trading volume yet is is priced inefficiently compared to its indicative value. This is most likely because Credit Suisse discontinued issuance of shares on the 21^{st} of February 2012. Therefore the long demand on the TVIX could not be met by newly issued notes and the price skyrocketed to a maximum efficiency premium of 89.43% on the 21^{st} of March 2012. Ever since this event the TVIX has traded at a higher premium than before. The average efficiency premium for the TVIX ETN was -0.08% before 21^{st} of February 2012 and 4.06% thereafter (if we start the 'after' average in April 2012 then it is 3.57%). It may be interesting for further research, to see how the efficiency premium of the other ETNs is affected by this event, as it makes such a event a realistic possibility for investors.

To summarize the results of the daily efficiency premium we can say that most of the VIX futures ETNs are not priced efficiently, at the daily level. We also recognize that those ETNs with the highest average trading volume seem to be more efficiently priced. Next we undergo a similar investigation using the intraday quote data for VIX futures ETNs and the intraday indicative value data.

4.2 Intraday efficiency

The intraday indicative value of the ETNs is reported at a 15 second frequency so we sample our 1 second interval ETN quote data at the same 15 second intervals at which their indicative values are reported [5]. We similarly define the intraday efficiency

[5] The 15 second interval for the indicative value is not always on the minute. Therefore using 1 second quote data and matching it in this way avoids any mismatches you may get if you sampled the ETN quotes at the 15 second frequency starting on the minute.

premium as:

$$EP_i = \frac{MV_i - IV_i}{IV_i}, \quad (2)$$

where EP_i is the efficiency premium at time i, MV_i is the mid-quote price of the ETN at time i and IV_i is the indicative value of the ETN at time i.

We then compute the mean efficiency premium and its significance p-value, for each day of the sample and across the entire sample. Table 4 reports the average of the intraday efficiency premium for the whole sample, its significance p-value and the proportion of the daily means of the intraday efficiency premiums that are significant at the 1% level. When using the intraday quote data and indicative value data the average efficiency premium is significant, at traditional level of significance, for all of the VIX futures ETNs. The daily means of the intraday efficiency premiums are also significantly different from zero most of the time. The proportion of days that the daily means of the intraday efficiency premiums are significant at the 1% level range from 79.85% to 95.96%, for all the ETNs.

Figures 2 and 3 depict the 10-Day moving average of the daily mean efficiency premium. From these figures we can also see that the daily mean efficiency premium usually is not zero. The figures also show that there are periods of time where the ETNs are priced very efficiently. Studying what is driving the variation in the efficiency of the VIX futures ETNs not may be of interest for further research.

The intraday results differ somewhat from the daily analysis of the efficiency premium, as even the highly traded VXX and XIV ETNs are priced inefficiently. It is important to note that the TVIX again displays a very large mean efficiency premium, as is expected due to the issuance halt event. If VIX futures ETNs are priced efficiently they should track the indicative value very closely. We can see from the daily and the intraday analysis that the ETNs are priced inefficiently with respect to their indicative values. In other words, VIX futures ETNs have significant tracking errors to their indicative values.

5 Consistency

In this section we investigate the consistency of the market prices of VIX futures ETNs to each other. This is an important analysis as many of the ETNs track the same index and should therefore be consistently priced. We cannot study the difference in their prices directly as different ETNs often have varying ways of calculating their indicative values. Therefore, we will extract the implied excess return index performance factor (IF) of each ETN and compare these instead. To get the IF we solve the indicative value formula (presented in the appendix) of each ETN for the excess return index performance factor. Then we substitute the market values in for the indicative values to get the IF.

For the VXX and VXZ the IF factor is given by:

$$IF_t^{ETN} = \frac{ETNMV_t}{ETNMV_{t-1}} \frac{1}{(1 - \frac{0.0089}{365})^d} - TBR_t, \tag{3}$$

where IF_t^{ETN} is the IF for the VXX or the VXZ, $ETNMV_t$ is the closing price of the ETN on day t, d is the number of calendar days since the last business day and TBR_t is the Treasury Bill Return on day t.

The IF factors for the VIIX, VIIZ, XIV, ZIV, TVIX and TVIZ are given by:

$$IF_t^{ETN} = 1 + \left(\frac{ETNMV_t}{ETNMV_{t-1}} \frac{1}{(1 - \frac{fee}{365})^d} - 1 - TBR_t \right) \frac{1}{L}, \quad (4)$$

where IF_t^{ETN} is the IF for one of the ETNs, $ETNMV_t$ is the closing price of that ETN, L is that leverage factor of the ETN and fee is the annual investor fee of that ETN.

Table 5 reports the differences of all possible combinations of the IFs [6]. Naturally we can only compare the IFs of ETNs with the same maturity underlying index, i.e. IF^VXX can only be compared to the IF of other ETNs that follow the short-term VIX futures index, be it the excess return or total return version. Panel A shows the mean differences between short-term ETN IFs and panel B reports the mean differences between the mid-term ETN IFs. If the ETNs are priced consistently then these differences should be insignificant. In the table we can see that the mean difference in IFs is insignificant for almost all of the pairs. However for any of the short-term pairs that include the XIV ETN the difference is significant. Looking at the mean difference and the p-values it seems that the mid-term ETNs are priced more consistently to each other, compared to the short-term ETNs.

Figures 4 and 5 plot the daily difference in IFs of the short-term and mid-term ETN pairs, respectively, against time. We can see that for most of the ETNs the difference is small apart from a few outliers. We can again observe the effect of the TVIX share creation suspension, as immediately after the 21st of February 2012 the pair differences that include TVIX become very large. From the diagrams it also seems that the mid-term ETNs are less consistently priced, compared to the short-term ETNs, which is the opposite of what we found when looking at the mean

[6] Some of the ETNs are not traded on some days, therefore there is no data on their market value that day, we ignore days where either of the ETNs in the pair do not have available prices

differences in table 5.

From table 5 and figures 4 and 5 we conjecture that, on average and at the daily level, all of the ETNs, apart from the TVIX and XIV ETN, are priced consistently. We have talked about the TVIX anomaly caused by the halt of note issuance, in section 4. The XIV may be priced inconsistently with respect to the other ETNs, due to its high demand and a lack of supply, during normal times. This would make sense as only the inverse ETNs, such as the XIV, have had positive average daily and holding period returns since inception (see table 1). This fits with the findings of Frijns, Gafiatullina, Tourani-Rad, and Fernandez-Perez (2016) who find that the VXX and XIV are not exact mirrors of each other, as institutional investors switch from long to short volatility exposure and vice versa.

6 Causality

In this section we explore the intraday two-way Granger causality between VIX futures ETNS and VIX futures, as well as between VIX futures ETN pairs. The two-way Granger causality tests will show us the lead-lag relationships and therefore the price discovery dynamics of the VIX futures ETN market.

6.1 Price discovery between VIX futures ETNs and VIX futures

Frijns, Tourani-Rad, and Webb (2015) show that, at the intraday level, VIX futures lead the VIX index in price discovery. However it may also be the case that the price discovery for VIX futures is taking place in the ETN market first, as the ETN market is much more liquid. Alexander and Korovilas (2013) show that the large hedging demand by VIX futures ETN asset managers could be causing VIX futures prices to change. Frijns, Tourani-Rad, and Webb (2015) show that the micro structure of the VIX futures market has changed significantly from before the VIX futures ETN inception to after. These results hint that the VIX futures ETNs have an impact on VIX futures, we now investigate this directly. Bollen, O'Neill, and Whaley (2016) have done something similar for just the VXX ETN and show that it leads VIX futures in price discovery, however we consider all of the ETNs in this paper.

There are many VIX derivatives available to investors for trading volatility. One of the derivatives may be favoured because of higher liquidity, less restraints (some funds are restricted from investing in options and/or futures), or lower trading costs. Whichever derivative is favoured will likely reflect market information first, for example Frijns, Gafiatullina, Tourani-Rad, and Fernandez-Perez (2016) show that the price discovery for the VXX and XIV ETN will happen that market which is favoured, at the time, by institutional investors. In this section we study price discovery relationship between VIX futures and VIX futures ETNs.

To access the lead-lag (price discovery) relationship between VIX futures and VIX futures ETNs we estimate the following VAR, at the intraday level each day and for each ETN:

$$\begin{aligned} lnMV_i &= \alpha_1 + \sum_{j=1}^{j=p+d} \phi_{1,j} lnMV_{i-j} + \sum_{j=1}^{j=p+d} \theta_{1,j} lnIV_{i-j} + \epsilon_{1,i+1} \\ lnIV_i &= \alpha_2 + \sum_{j=1}^{j=p+d} \phi_{2,j} lnMV_{i-j} + \sum_{j=1}^{j=p+d} \theta_{2,j} lnIV_{i-j} + \epsilon_{2,i+1}, \end{aligned} \tag{5}$$

where α_1, α_2, $\phi_{1,j}$, $\phi_{2,j}$, $\theta_{1,j}$ and $\theta_{2,j}$ are the estimated model coefficients, MV_i and MV_{i-j} are the log mid-quote prices at time i and $i-j$ respectively and IV_i and

IV_{i-j} are the log indicative values at time i and $i - j$ respectively. We use the intraday indicative value to study the price discovery relationship between the VIX futures ETNs and VIX futures because the indicative value will only change when the underlying VIX futures prices change, during the trading day. This also allows us to investigate the relationship between the ETN and all of its underlying futures prices simultaneously without having to create our own proxy VIX futures position for this. The drawback of this approach is that we are limited to a 15 second sampling frequency, as this is the frequency at which the indicative value is available.

The optimal lag length, p in equation 5, is determined by minimizing the average daily Schwartz Information Criterion (SIC), up to 12 lags. If there is significant autocorrelation in the model residuals then more lags are added until this is resolved. We then add d lags, where d is the maximum of the expected order of integration of the indicative value and the quote time series (always 1 in our analysis). Our methodology for dealing with concerns of non stationarity and cointegration comes from Toda and Yamamoto (1995). We use the levels of the data regardless of whether they may or may not be stationary or cointegrated. Following Toda and Yamamoto (1995) we add d extra lags, as they show that this will prevent any pretest bias when it comes to calculating the Granger causality statistics. When using their methodology to do a Wald-test, for calculating the Granger causality statistics, we do not include the extra d lag coefficients, it is treated as a exogenous variable.

In table 6 we report the results of the Granger causality tests. We report the mean of the daily Granger causality statistics over the sample period and the percentage of days where the Granger causality is significant, at traditional levels. We find that for all of the ETNs the mean Granger causality statistic from the market value to the indicative value is very large, ranging from 399.51 to 1032.16. For all ETNs we find that the percentage of significant daily Granger causal effects from the market value to the indicative value is very close to 100% at traditional levels of significance, and for all of the ETNs. We also find that the average Granger causality statistic from the indicative value to the market value is much smaller, ranging from 5.76 to 43.75, for the different ETNs. We also find that the percentages of significant daily Granger causality statistics for this direction of the relationship are much lower, ranging from 1.68% (23.26%) to 18.60% (58.38%) at the 1% (10%) level of significance. From table 6 we conclude that all of the ETNs lead the VIX futures in price discovery. This is consistent with the finding of Bollen, O'Neill, and Whaley (2016), who show that the VXX leads VIX futures in price discovery.

We also investigate the time variation of the intraday price discovery relationship between VIX futures and VIX futures ETNs by adopting the methodology from Frijns, Tourani-Rad, and Webb (2015). We define the log ratio of the Granger causality statistics as

$$LogRatioGC_{t,i} = \log\left(\frac{GC_{t,i}^{MVtoIV}}{GC_{t,i}^{IVtoMV}}\right), \tag{6}$$

where $GC_{t,i}^{MVtoIV}$ is the Granger causality statistic from the VIX futures ETN i to VIX futures on day t and $GC_{t,i}^{IVtoMV}$ is the Granger causality statistic from the VIX futures to the VIX futures ETN i on day t.

We plot the 10-day moving average of the log ratios of the Granger causality statistics for the short-term and mid-term VIX futures ETNs, in figures 6 and 7 respectively. In figure 6 we can see that the Causality between short-term VIX futures ETNs and VIX futures does vary over time but the log ratios do stay within a band of 3-7 on most days. This shows that the price discovery is in the ETN market throughout time, this supports the findings in table 6. The TVIX ETN log ratio of Granger causality statistics departs from the norm in the second half of 2012, this may be caused by the halt of share creation by the issuer which we discussed in section 4.1. Figure 7 shows that the mid-term ETN log ratios are always positive and usually between 2 and 6. This again shows that the price discovery is happening mostly in the VIX futures ETNs rather than the VIX futures. For further research it may be interesting to see what drives the time variation in the informational dominance of the VIX futures ETNs over the VIX futures. This could be done similarly to Frijns, Tourani-Rad, and Webb (2015) and Frijns, Gafiatullina, Tourani-Rad, and Fernandez-Perez (2016) by regressing the log ratios on possible determinants, such as return to the S&P 500 index, change in VIX, a ratio of trading volume of the ETNs and VIX futures, a ratio of the bid-ask spread on futures and ETNs, among others. Interesting explanatory variables not used by Frijns, Tourani-Rad, and Webb (2015) or Frijns, Gafiatullina, Tourani-Rad, and Fernandez-Perez (2016) may be a proxy measure of hedging demand by ETN issuers, such as the one constructed by Alexander and Korovilas (2013), and trader position data from the Traders in Financial Futures (TFF) reports published by the U.S. Commodity Futures Trading Commission (CFTC).

Combining the evidence from table 6 and figures 6 and 7 we can conclude there is a one way Granger causality relationship from VIX futures ETNs to VIX futures. This tells us that the price discovery for these markets leads in the VIX futures ETN market. We can therefore confirm that the tail (VIX futures ETNs) is truly wagging the dog (VIX futures), as suggested by Alexander and Korovilas (2013) and shown for the VXX in Bollen, O'Neill, and Whaley (2016).

The results in this section could explain the significant efficiency premium that we have found at the daily and intraday level (see section 4). The efficiency premium is a measure of contemporaneous efficiency. Since the ETN market is leading the futures market we would expect a contemporaneous efficiency premium that is significantly different to zero.

Frijns, Tourani-Rad, and Webb (2015) show that price discovery for the VIX index and VIX futures is in the futures markets. Combining our results with those of Frijns, Tourani-Rad, and Webb (2015) we can conjecture that price discovery for the VIX index, VIX futures and VIX futures ETNs happens in the VIX futures ETNs first followed by VIX futures and then the VIX index.

In an open letter to investors on June 29th 2013, Mark Wiedman, global head of iShares, offered a declaration explaining why ETFs are often trading at discount or premium to their Net Asset Value[7]. He says "More and more, ETFs are becoming the true market". He also states "The ETF price can become the true price for that market, and the underlying assets may eventually catch up with any gap...". Although the letter is in regard to ETFs it supports our finding that the VIX futures ETNs are leading VIX futures in price discovery. It is likely a product of the easy of trading the VIX futures ETNs compared to the VIX futures contracts.

6.2 Price discovery between VIX futures ETNs

We have investigated the intraday price discovery relationship between VIX futures and VIX futures ETNs, we now turn to the price discovery relationship between VIX

[7]The indicative value for ETNs synonymous to Net Asset Value for ETFs.

futures ETN pairs. Frijns et al. (2016) study the price discovery relationship of one of these pairs, the VXX and XIV. They find that the price discovery between these two pairs is time varying, which we confirm, however this may be the case for other ETN pairs too. If there is strong one way Granger causality in an ETN pair then price discovery happens in one ETN before the other.

To access the relationship between VIX futures ETN pairs, at the intraday level, we estimate the following VAR each day and for each ETN pair:

$$\begin{aligned} lnMV_{1,i} &= \alpha_1 + \sum_{j=1}^{j=p+d} \phi_{1,j} lnMV_{1,i-j} + \sum_{j=1}^{j=p+d} \theta_{1,j} lnMV_{2,i-j} + \epsilon_{1,i+1} \\ lnMV_{2,i} &= \alpha_2 + \sum_{j=1}^{j=p+d} \phi_{2,j} lnMV_{2,i-j} + \sum_{j=1}^{j=p+d} \theta_{2,j} lnMV_{1,i-j} + \epsilon_{2,i+1}, \end{aligned} \tag{7}$$

where α_1, α_2, $\phi_{1,j}$, $\phi_{2,j}$, $\theta_{1,j}$ and $\theta_{2,j}$ are the estimated model coefficients, $MV_{1,i}$ and $MV_{1,i-j}$ are the log mid-quote prices of the first ETN at time i and $i-j$ respectively and $MV_{2,i}$ and $MV_{2,i-j}$ are the log mid-quote prices of the second ETN at time i and $i-j$ respectively. We again eliminate any pretest bias by following the methodology outlined in Toda and Yamamoto (1995), as in section 6.1.

Table 7 reports the mean daily Granger causality statistics and percentage of daily Granger causality statistics that are significant for both directions for each ETN pair. We can see that the mean daily Granger causality statistics are large in both directions for all the ETN pairs, ranging from 122.24 to 568.59. We can also see that for all of the ETN pairs the percentage of significant daily Granger causality statistics is high in both directions for all of the ETNs, ranging from 70.08% (88.47%) to 99.92% (100.00%) at the 1% (10%) level of significance. Overall this table shows that the lead-lag relationship for VIX futures ETN pairs seems to be a strong two way relationship, meaning the price discovery happens in the ETNs contemporaneously[8].

Again we want to investigate the time variation in the causality relationship. As in equation (6) we define the log ratio of the Granger causality statistics as:

$$LogRatioGC_t = log\left(\frac{GC_t^{MV_1toMV_2}}{GC_t^{MV_2toMV_1}}\right), \quad (8)$$

where $GC_t^{MV_1toMV_2}$ is the Granger causality statistic for the causal effect from the first ETN to the second on day t and $GC_t^{MV_2toMV_1}$ is the Granger causality statistic for the causal effect from the second ETN to the first on day t.

Figures 8 and 9 plot the time series of the 10-day moving average of the log ratio of the Granger causality statistics for the short-term and mid-term ETN pairs, respectively. We can see that for all of the ETN pairs the log ratio is time varying. The figure shows that most of the time there is a two way lead-lag relationship between the ETNs in the ETN pairs. However we can also see that there seem to be time periods where the relationship is stronger one way or the other. This is especially the case for any pair that includes the XIV ETN, likely due to the trading behaviour of institutional investors. Institutional investors tend to be better informed and so when volatility is high they will be long long exposure volatility ETNs and this will result in the price discovery taking place in the long exposure ETNs, and vice versa (Frijns, Gafiatullina, Tourani-Rad, and Fernandez-Perez, 2016). It would be interesting for future research to examine what drives these changes in the relationships, as in Frijns, Gafiatullina, Tourani-Rad, and Fernandez-Perez (2016), for all the ETN pairs. The time variation in the price discovery relationship between mid-term ETN pairs seems smaller but can still be large at times. The mid-term ETNs have not been studied

[8] Again we can see the effect of the halt of share creation for the TVIX, as any pair which includes the TVIX has a slightly more one way causality.

much in the literature likely due to their smaller market share, but it would be interesting to see what drives the variation in the price discovery relationships for these ETNs too.

7 Conclusion

In this paper we examine the tracking efficiency, pricing consistency and causality of the VIX futures ETN market. We have found that most of the VIX futures ETNs are not priced efficiently with respect to their indicative values at the daily level. The ETNs that were priced efficiently at the daily level were those which have non-leveraged to the underlying index and that are very liquid. At the intraday level none of the ETNs are efficiently priced. The intraday data is not at risk of information aggregation and therefore has more power than the daily data. Therefore we conclude that the VIX futures ETNs do not efficiently track their indicative values.

We then investigated the VIX futures ETNs price consistency with respect to each other. To do this we calculated the index returns implied by the ETN market prices. Comparing the market prices would not make much sense as each ETN has slightly different methodologies for their indicative values. We find that the VIX futures ETNs are priced consistently at the daily level, as the IFs do not differ significantly. It may interesting to further research this at the intraday level.

We also investigated the Granger causality between VIX futures and VIX futures ETNs, at the intraday level. We find that the ETN market leads the futures market, confirming that the 'tail is wagging the dog' as Bollen, O'Neill, and Whaley (2016) shows for the VXX. This also builds on the findings of Fernandez-Perez, Frijns, Tourani-Rad, and Webb (2015), who find that the micro-structure of the VIX futures market changes dramatically after the introduction of VIX futures ETNs. Given the findings of Frijns et al. (2015), that VIX futures lead the VIX index, we could conjecture that VIX futures ETNs lead VIX futures which lead the VIX index. Although ETNs lead futures throughout our sample, the magnitude of the relationship varies through time. Investigating what drives this time variation could be of further interest, as Frijns, Tourani-Rad, and Webb (2015) do for the time variation in the price discovery relationship between the VIX and VIX futures. The price discovery relationship we have uncovered could also explain our result of the contemporaneous tracking inefficiency of the ETN market prices relative to their indicative values.

When investigating the price discovery relationships of the ETNs with respect to each other, we find that price discovery happens contemporaneously. Again this price discovery relationship between ETN pairs varies over time, fluctuating around a even two way Granger causality (log ratio of Granger causality statistics of 0), as Frijns et al. (2016) show for the VXX and XIV. Investigating the drivers of the time variation may provide further results of interest.

Collectively our findings will help practitioners, policy makers and academics further understand the dynamics of the young and rapidly growing volatility market. VIX futures ETNs are some of the most traded volatility derivatives available, therefore fully understanding this market is very important. Practitioners and/or researchers may be able to derive profitable trading strategies from the insights of this paper.

Appendix

A.1 Indicative value methodology

The indicative value methodologies displayed in this section are summarized mathematical representations of the specifications in the respective ETN prospectuses.

The closing indicative values of the VXX and VXZ are defined as

$$ETNIV_t = ETNIV_{t-1}\left(1 - \frac{0.0089}{365}\right)^d \left(\frac{TRI_t}{TRI_{t-1}}\right), \tag{9}$$

where $ETNIV_t$ is the closing indicative value of the VXX or VXZ on day t, TRI_t is the closing value either the SPVXSTR index on day t, when considering the VXX, or the SPVXMT index on day t, when considering the VXZ and d is the number of days since the last index business day.

The closing indicative value of the VIIX, VIIZ, XIV, ZIV, TIIX and TVIZ are defined as

$$ETNIV_t = ETNIV_{t-1}\left(1 - \frac{fee}{365}\right)^d \left[1 + TBR_t + L\left(\frac{ERI_t}{ERI_{t-1} - 1}\right)\right] \tag{10}$$

where $ETNIV_t$ is the closing indicative value of the VIIX, VIIZ, XIV, ZIV, TIIX or TVIZ on day t and ERI_t is the closing value of either the SPVXSER index on day t, when considering the VIIX, XIV, or TVIX ETNs, and the SPVXMER index on day t, when considering the VIIZ, ZIV or TVIZ. The TBR_t is Treasury Bill return on day t defined as

$$TBR_t = \left(\frac{1}{1 - Tbill_{t-1}\frac{91}{360}}\right)^{\frac{d}{91}} - 1, \tag{11}$$

where $Tbill_{t-1}$ is the three month Treasury Bill rate on the prior index business day reported by Bloomberg and d is the number of calendar days since the prior index business day.

The indicative value of the XVIX ETN is defined as

$$XVIXIV_t = XVIXIV_{t-1}\left[1 + TBR_t - 0.5\left(\frac{SPVXSER_t}{SPVXSER_{t-1}} - 1\right) + \left(\frac{SPVXMER_t}{SPVXMER_{t-1}} - 1\right) - \left(\frac{0.0085}{365}\right)\right]^d, \tag{12}$$

where $XVIXIV_t$ is the closing indicative value of the XVIX on day t, $SPVXSER_t$ is the closing value of the SPVXSER index on day t and $SPVXMER_t$ is the closing value of the SPVXMER index on day t.

The indicative value of the XXV ETN is defined as

$$XXVIV_t = XXVIV_0\left(1 - \left(\frac{SPVXSER_t}{SPVXSER_0} - 1\right)\right) + IA_{0,t} - FA_{0,t}, \tag{13}$$

where $XXVIV_t$ is the closing indicative value of the XXV on day t, $SPVXSER_0$ is the value of the SPVXSER index at the time of inception of the XXV ETN, $IA_{0,t}$ is the interest accrued since the inception of the ETN defined as

$$IA_{0,t} = \sum_{j=1}^{t} XXV_{j-1}\left(\frac{TBBR_j}{360}d_j\right), \tag{14}$$

where $TBBR_j$ is the 28-day Tbill rate on day j. $FA_{0,t}$ in equation (13) is the accrued fees since the inception of the ETN, defined as

$$FA_{0,t} = \sum_{i=1}^{t} XXV_{i-1}\frac{0.0089}{365}. \tag{15}$$

The CVOL ETN indicative value is calculated by

$$CVOLIV_t = CVOLIV_{t-1} \times \left(\frac{CVOLTR_t}{CVOLTR_{t-1}}\right) \times \left(1 - \frac{0.0115}{365}d\right) \tag{16}$$

where where $CVOLIV_t$ is the closing indicative value of the CVOL on day t and $CVOLTR_t$ is the Citi Volatility index Total Return index (CVOLTR) value on day t. The CVOLTR index is an index created by Citigroup that mimics dynamic position in the 3rd and 4th nearest maturing VIX futures contracts as well as the S&P 500 Total return index (SPX). [9]

[9] For more details on the calculation of the CVOLTR please refer to the CVOL prospectus available at http://www.c-tracksetns.com/MediaLibrary/d794c081-a732-4431-80c3-cbc08ac24464/Citi.Volatility.C.Tracks.Pricing.Supplement.Amendment.No.9.PDF

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Table 1: **VIX futures ETN market summary** This table shows a summary for the VIX futures ETNs that are still traded today. It shows the issuer, inception date, leverage with respect to the underlying index, whether the ETN has a Short-Term or Mid-Term index as the underlying and the investor fee. We also report the mean daily return, standard deviation of daily returns , the holding period return HPR from 20^{th} of December, 2010 to the 31^{st} of March, 2016 and the Market Capitaliztion as of the 31^{st} of March, 2016, for each of the ETNs in this table.

ETN Ticker	Issuer	Inception	Leverage Multiplier	ST or MT index	Fee	Mean Daily Return	St. Dev. Return	HPR	Market Cap ($000)	Average Daily Trading Volume ($000)
VXX	Barclays	29/01/2009	1	ST	0.89%	−0.18%	4.07%	−97.06%	1,130,420.00	1,092,338.97
VXZ	Barclays	29/01/2009	1	MT	0.89%	−0.11%	2.03%	−82.96%	41,362.40	17,475.04
XIV	Credit Suisss	29/11/2010	-1	ST	1.35%	0.14%	4.07%	113.27%	898,783.00	357,253.87
ZIV	Credit Suisss	29/11/2010	-1	MT	1.35%	0.08%	2.01%	189.75%	90,002.70	2,138.99
VIIX	Credit Suisss	29/11/2010	1	ST	0.89%	−0.19%	4.11%	−97.00%	7,645.40	6,465.01
VIIZ	Credit Suisss	29/11/2010	1	MT	0.89%	−0.07%	1.94%	−82.75%	607.6	179.72
TVIX	Credit Suisss	29/11/2010	2	ST	1.65%	−0.43%	7.74%	−99.99%	456,023.00	91,119.51
TVIZ	Credit Suisss	29/11/2010	2	MT	1.65%	−0.23%	4.04%	−98.39%	816.5	205.62
XXV	Barclays	16/07/2010	-1	ST	0.89%	0.02%	0.69%	14.64%	684.3	1,634.20
XVZ	Barclays	17/08/2011	Dynamic	ST & MT	0.95%	−0.04%	1.10%	−47.18%	9,409.40	1,550.64
XVIX	UBS	30/11/2010	Dynamic	ST & MT	0.85%	−0.05%	0.77%	−36.41%	11,842.50	284.22
CVOL	Citi	17/11/2010	Dynamic	CVOLTR	1.15%	−0.35%	6.61%	−99.95%	2,453.50	248.10

Table 2: **Potential un-hedged profit of ETN issuers** This table shows the potential profit to the ETN issuer, if they did not hedge their ETN exposures other than through inverse ETNs, by ETN and issuer totals. The potential profit is calculated using the change in shares outstanding multiplied by the closing indicative value, each day. Then summing this across the whole sample, adding the initial number of shares issued times the initial indicative value and subtracting the number of shares outstanding times the closing indicative value on the 31st of March 2016.

ETN ticker	Issuer	Potential Profit	Total Potential Profit for Issuer
	Barclays Capital iPath		
VXX		5,822,950,802.10	
VXZ		340,418,370.00	
XXV		−16,228,510.00	
XVZ		164,649,462.10	
	-		6,311,790,124.20
	Credit Suisse Velocity Shares		
XIV		−672,953,998.00	
ZIV		−22,395,643.30	
VIIX		68,457,203.80	
VIIZ		9,325,272.00	
TVIX		1,771,864,922.10	
TVIZ		13,179,007.20	
			1,167,476,763.80
XVIX	UBS E-TRACS	−8,071,436.30	−8,071,436.30
CVOL	Citi Bank C-TRACS	658,298,500.00	658,298,500.00

Table 3: **Daily VIX futures ETNs efficiency premium** This table summarizes the significance of the daily efficiency premium (EP), as defined in equation (1). The table shows the mean daily efficiency premium for each ETN, as defined in equation (1), its standard deviation, p-value and 95% confidence interval. The table also reports the mean daily trading volume (in 1,000s of shares traded) for each ETN.

ETN Ticker	Mean EP	Volatility	P-value	Avg. Daily Volume (1000's)	Confidence Interval 95%	
VXX	−0.01%	0.93%	0.5167	25250.47	−0.06%	0.03%
VXZ	−0.09%	0.57%	0.0000	645.64	−0.12%	−0.07%
XIV	0.03%	1.06%	0.2784	13986.70	−0.03%	0.09%
ZIV	0.10%	0.69%	0.0000	59.20	0.06%	0.14%
VIIX	−0.02%	0.97%	0.5324	89.40	−0.07%	0.04%
VIIZ	−0.03%	1.20%	0.3946	5.70	−0.11%	0.04%
TVIX	3.11%	5.72%	0.0000	4325.54	2.80%	3.42%
TVIZ	−0.16%	1.65%	0.0009	2.84	−0.25%	−0.06%
XXV	−0.03%	0.18%	0.0000	47.66	−0.04%	−0.01%
XVZ	−0.04%	0.54%	0.0079	35.79	−0.07%	−0.01%
XVIX	−0.07%	0.58%	0.0000	13.21	−0.11%	−0.04%
CVOL	0.47%	5.99%	0.0042	54.70	0.15%	0.79%

Table 4: **Intraday VIX futures ETNs efficiency premium** This table summarizes the significance of the intraday efficiency premium (EP), as defined in equation (2). It shows the mean intraday efficiency premium and its significance p-value for each ETN. The table also shows the percentage of days in the sample that the daily mean of the intraday efficiency premium is is significant at the 1% level of significance.

ETN Ticker	Mean EP	P-value	% of sign. daily Mean
VXX	0.0543%	0.0000	93.90%
VXZ	0.0424%	0.0000	94.82%
XIV	−0.0362%	0.0000	84.18%
ZIV	−0.0114%	0.0000	86.28%
VIIX	0.0297%	0.0000	79.85%
VIIZ	0.0204%	0.0000	82.45%
TVIX	4.2728%	0.0000	95.06%
TVIZ	0.0275%	0.0000	87.14%
XXV	−0.0162%	0.0000	95.96%

Table 5: **VIX futures ETN IF consistency** This table shows the mean of the daily difference in implied index performance factors (IFs), as defined in section 5, its standard deviations and p-value.

ETN Pair	Mean Pair Difference	Std. dev. Price Diff	P-value
Panel A:			
VIIX - VXX	0.00%	0.32%	0.9036
XIV - VXX	0.03%	0.33%	0.0002
TVIX - VXX	−0.03%	0.83%	0.1849
XIV - VIIX	0.03%	0.41%	0.0037
TVIX - VIIX	−0.03%	0.90%	0.2238
TVIX - XIV	−0.06%	0.90%	0.0105
Panel B:			
VIIZ - VXZ	0.01%	1.16%	0.8883
ZIV - VXZ	0.00%	0.58%	0.7796
TVIZ - VXZ	0.00%	0.83%	0.8483
ZIV - VIIZ	−0.01%	1.13%	0.8461
TVIZ- VIIZ	0.00%	1.07%	0.9614
TVIZ - ZIV	0.00%	0.91%	0.9447

Table 6: **Two-way Granger causality between VIX futures ETNs and VIX futures** This table presents the results of the price discovery analysis between VIX futures and VIX futures ETNs. The table reports the mean daily Granger causality statistics from (to) each ETN and to (from) its indicative value. The table also reports the percentage of days that the Granger causality statistic is significant at the 1%, 5% and 10% levels of significance, for both directions each ETN.

From	To	Mean Granger Causality Statistic	Percentage of Significant Daily Granger		
			$\alpha = 0.01$	$\alpha = 0.05$	$\alpha = 0.10$
VXXIV	VXX	5.76	1.68%	14.87%	23.26%
VXX	VXXIV	1032.16	99.85%	99.92%	99.92%
VXZIV	VXZ	12.13	18.60%	48.86%	58.38%
VXZ	VXZIV	456.93	99.85%	99.92%	99.92%
XIVIV	XIV	6.62	3.71%	18.91%	29.54%
XIV	XIVIV	766.92	99.13%	99.75%	99.88%
ZIVIV	ZIV	10.23	11.50%	40.67%	49.32%
ZIV	ZIVIV	436.58	99.13%	99.63%	99.75%
VIIXIV	VIIX	6.88	3.58%	16.19%	24.47%
VIIX	VIIXIV	855.41	98.76%	99.51%	99.51%
VIIZIV	VIIZ	13.01	10.14%	32.88%	42.27%
VIIZ	VIIZIV	480.11	97.90%	99.01%	99.26%
TVIXIV	TVIX	13.31	18.42%	36.96%	44.50%
TVIX	TVIXIV	565.59	98.39%	99.38%	99.63%
TVIZIV	TVIZ	9.46	8.53%	33.00%	42.15%
TVIZ	TVIZIV	481.81	98.76%	99.51%	99.51%

Table 7: **Two-way Granger causality of ETN Pairs** This table presents the results for the price discovery between VIX futures ETN pairs. The table reports the mean daily Granger causality statistics for each ETN pair. The table also reports percentage of days that the causality statistic is significant at the 1%, 5% and 10% levels of significance, for each ETN pair in both directions. Panel A reports the short-term ETN results and Panel B the mid-term.

From	To	Mean Granger Causality Statistic	Percentage of Significant Daily Granger $\alpha = 0.01$	$\alpha = 0.05$	$\alpha = 0.10$
Panel A:					
VIIX	VXX	341.43	98.42%	98.87%	98.87%
VXX	VIIX	348.85	95.33%	98.19%	98.64%
XIV	VXX	404.84	96.38%	98.42%	98.72%
VXX	XIV	568.98	99.10%	99.62%	99.77%
TVIX	VXX	122.24	72.95%	87.72%	90.88%
VXX	TVIX	548.59	99.92%	100.00%	100.00%
XIV	VIIX	329.77	91.18%	96.53%	97.59%
VIIX	XIV	554.74	98.04%	98.94%	99.10%
TVIX	VIIX	144.16	70.08%	85.15%	88.47%
VIIX	TVIX	504.52	98.34%	98.79%	98.79%
XIV	TVIX	491.17	96.83%	98.72%	99.10%
TVIX	XIV	228.03	75.58%	88.92%	92.01%
Panel B:					
VIIZ	VXZ	189.69	96.38%	97.59%	97.74%
VXZ	VIIZ	190.87	88.17%	96.31%	96.99%
ZIV	VXZ	174.61	96.91%	98.42%	98.57%
VXZ	ZIV	211.76	93.07%	97.51%	98.12%
TVIZ	VXZ	232.40	97.06%	98.57%	98.72%
VXZ	TVIZ	182.25	83.35%	93.59%	95.18%
ZIV	VIIZ	232.61	92.69%	97.81%	98.42%
VIIZ	ZIV	236.61	93.44%	97.06%	97.51%
TVIZ	VIIZ	304.58	94.80%	98.12%	98.72%
VIIZ	TVIZ	219.21	86.21%	94.20%	95.33%
ZIV	TVIZ	169.02	90.28%	96.76%	97.51%
TVIZ	ZIV	258.06	97.14%	98.42%	98.57%

Figure 1: **Total dollar trading volume and market capitalization** In the top panel of this figure we plot the 10-day moving average of the total daily dollar trading volume of the VIX futures ETN market. In the second panel we plot the 10-day moving average of the daily total market capitalization of the VIX futures ETN market.

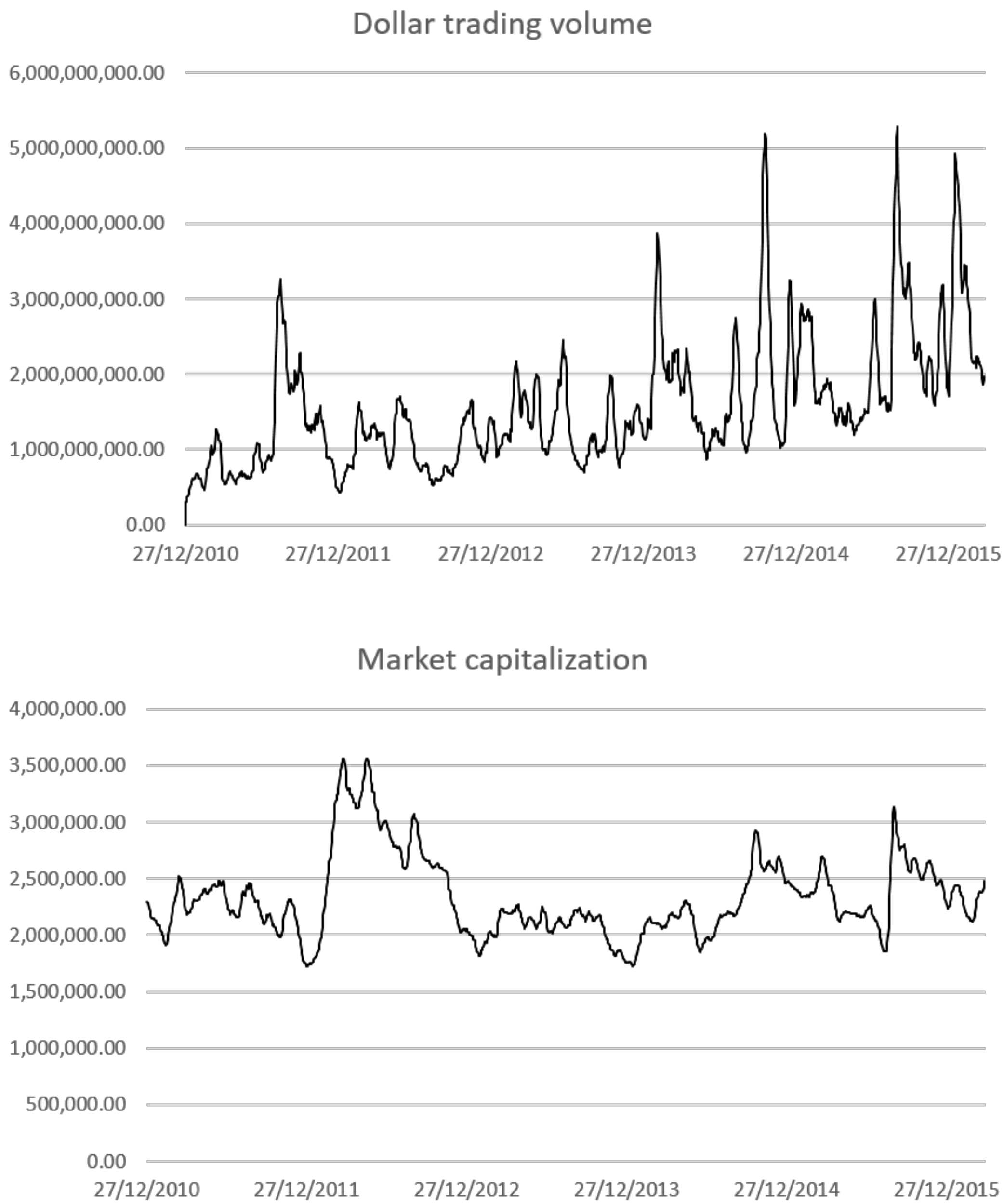

Figure 2: **Intraday EP: short-term ETNs** This figure depicts the 10-day moving average of the intraday efficiency premium, as defined in section 4.2, for the short-term ETNs.

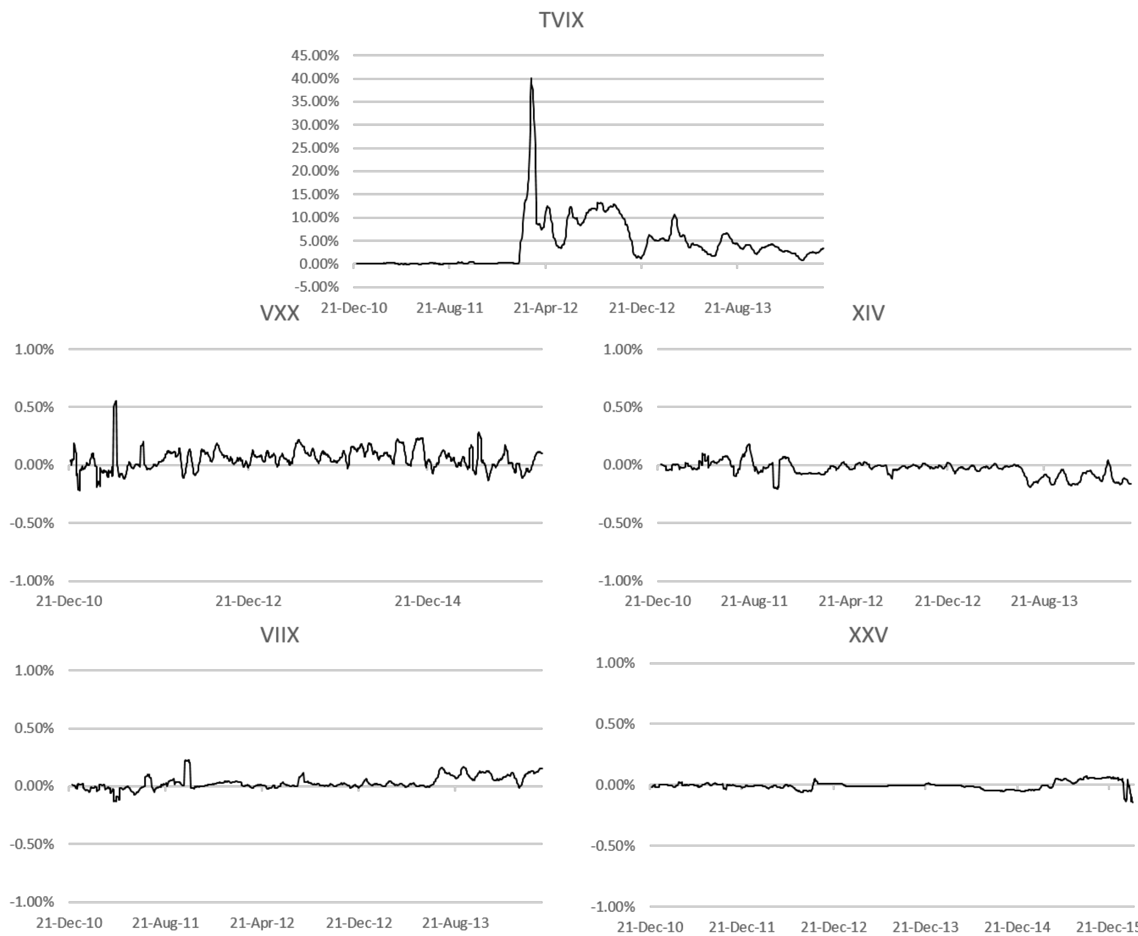

Figure 3: **Intraday EP: mid-term ETNs** This figure depicts the 10-day moving average of the intraday efficiency premium, as defined in section 4.2, for the mid-term ETNs.

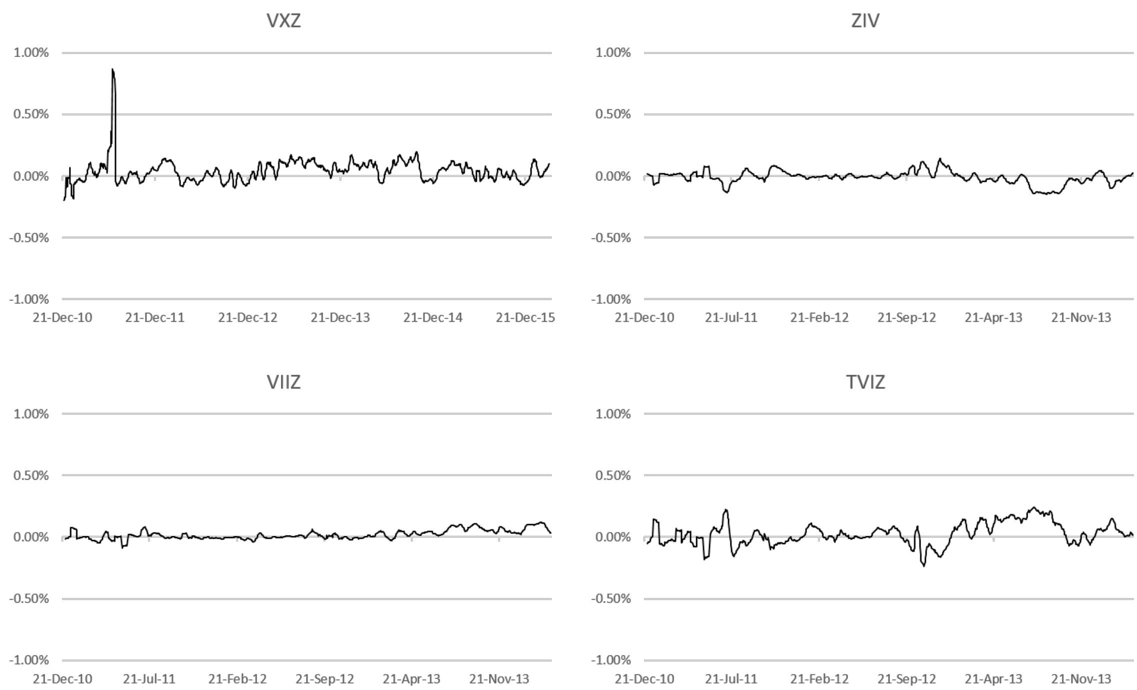

Figure 4: **Daily difference in IF: short-term ETNs** This figure plots the difference in implied excess return index factor performance (IF) of each ETN pair, as defined in section 5, for short-term ETNs.

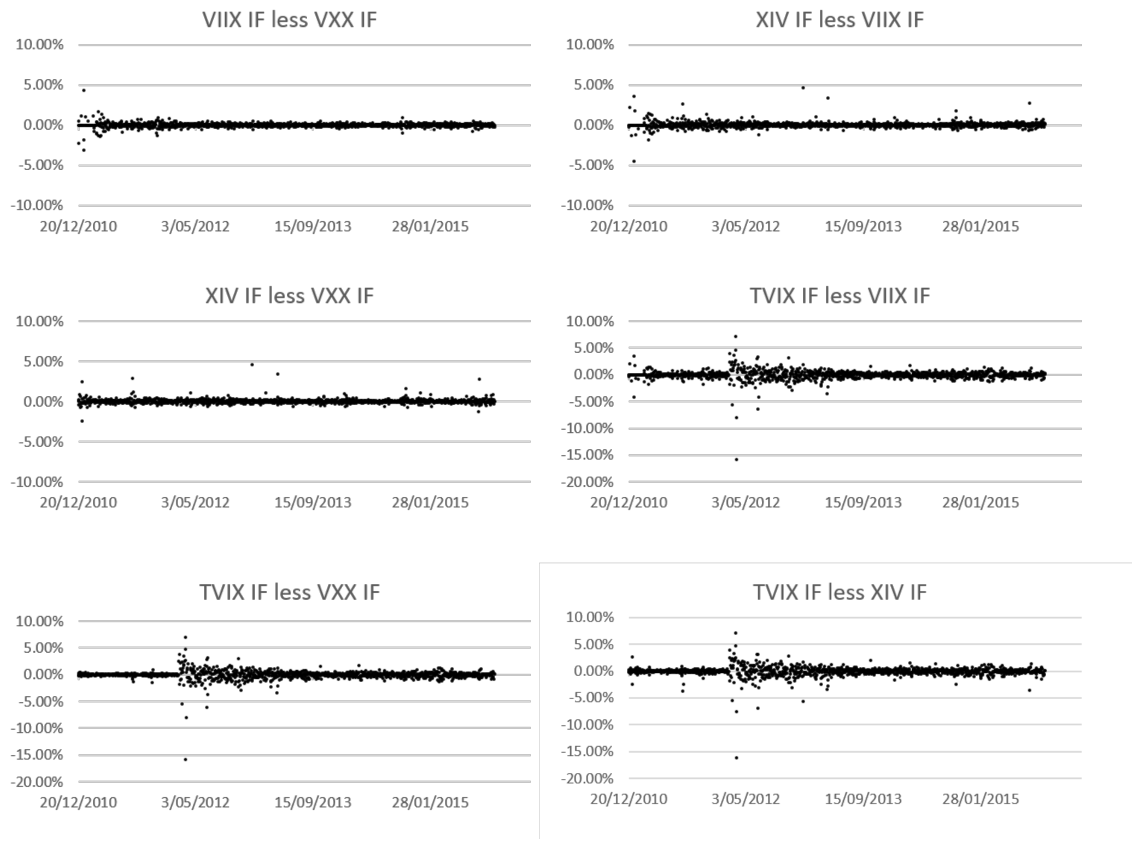

Figure 5: **Daily Difference in IF: Mid-Term ETNs** This figure plots the difference in implied excess return index factor performance(IF) of each ETN pair, as defined in section 5, for mid-term ETNs.

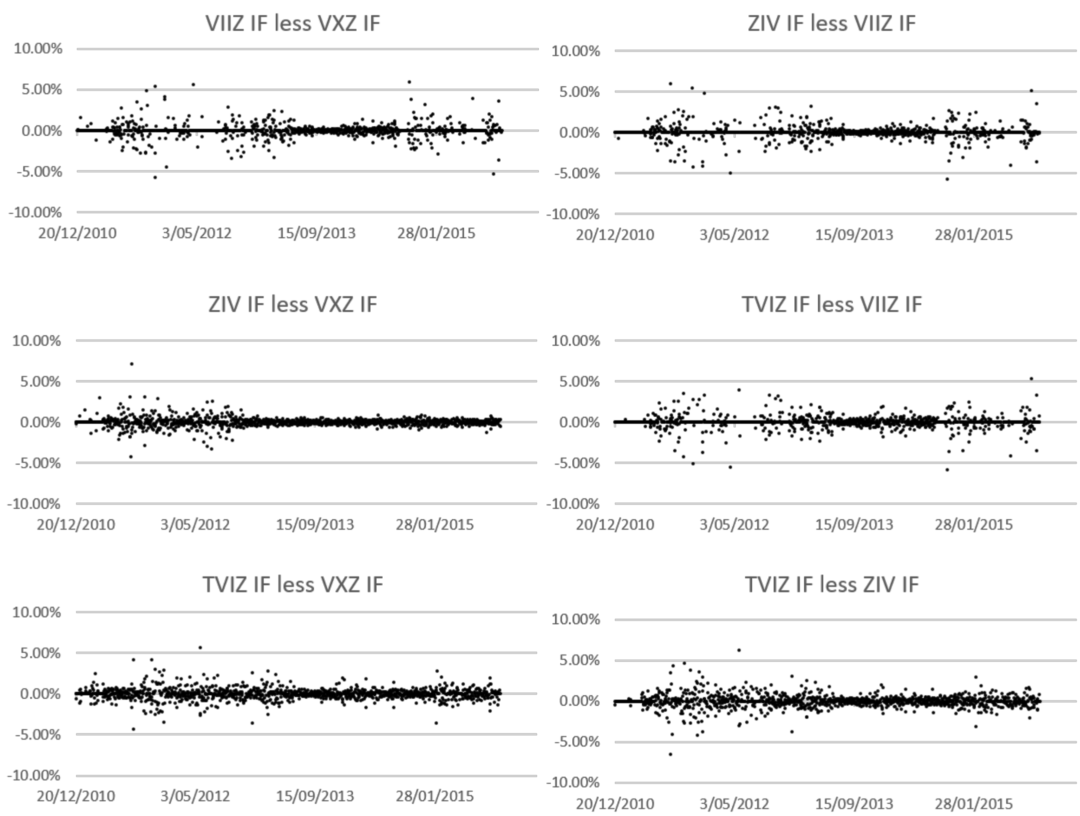

Figure 6: **Time variation in VIX futures ETN and VIX futures causality ratios: short-term ETNs** This figure plots the 10-day moving average of the log Granger Causality ratio, as defined in equation (6), for the short-term ETNs.

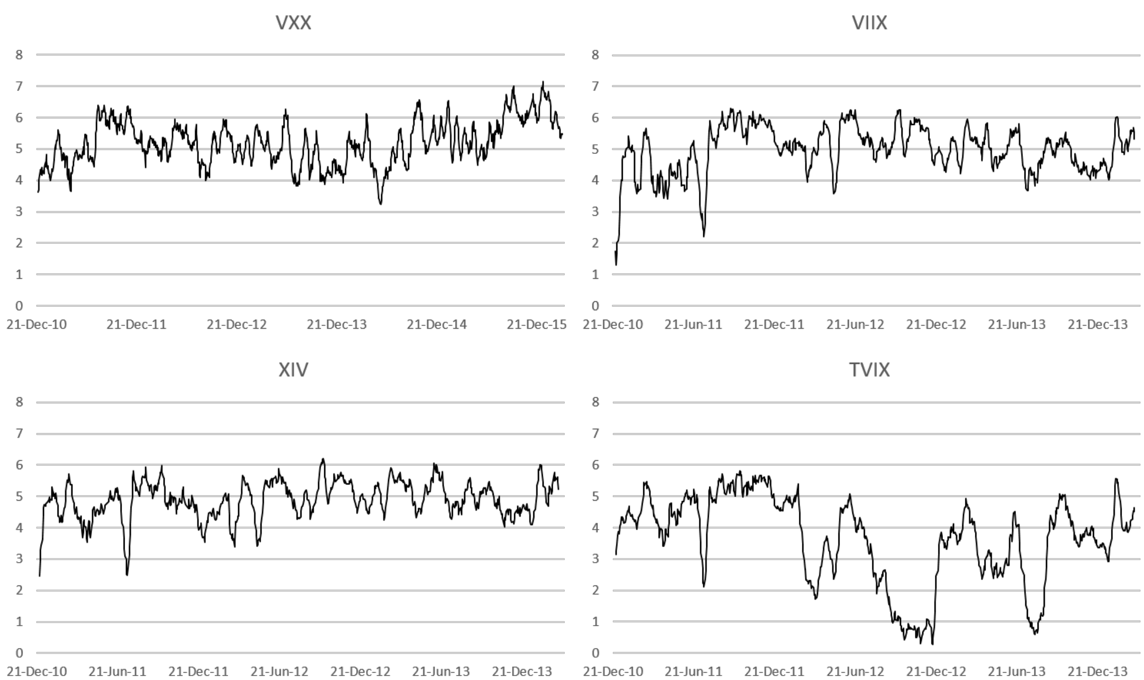

Figure 7: **Time variation in VIX futures ETN and VIX futures causality ratios: mid-term ETNs** This figure plots the 10-day moving average of the log Granger Causality ratio, as defined in equation (6), for the mid-term ETNs.

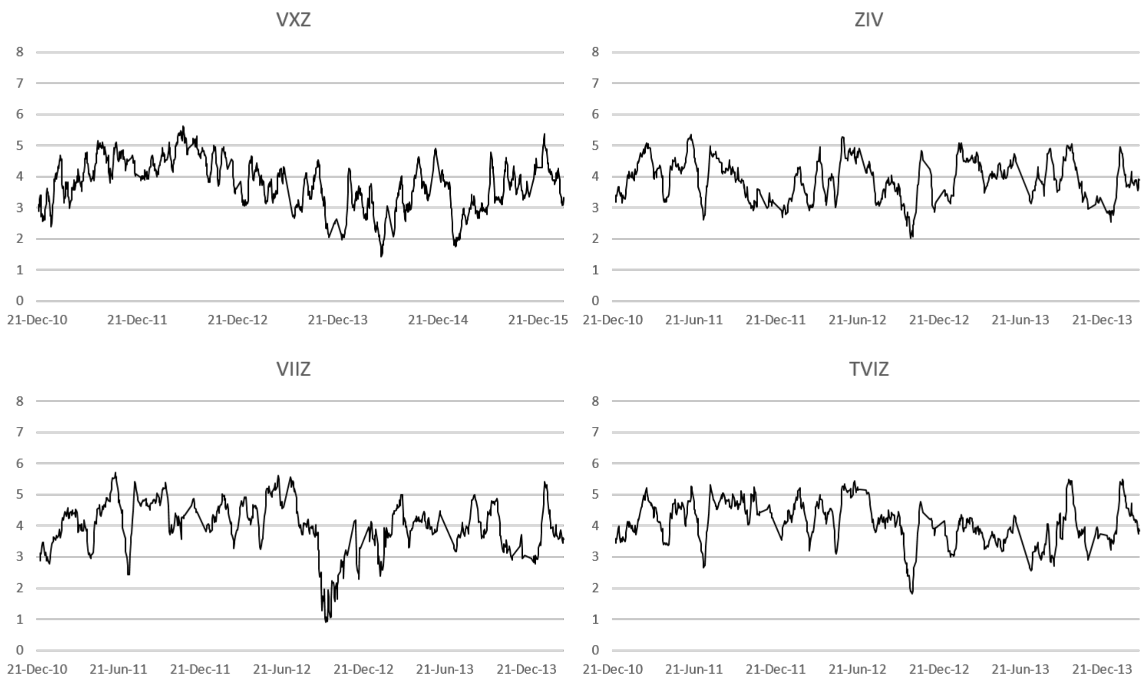

Figure 8: **Time variation in VIX futures ETN pair causality ratios: short-term ETNs** This figure plots the 10-day moving average of the log Granger Causality ratio, as defined in equation (8), for the short-term ETNs.

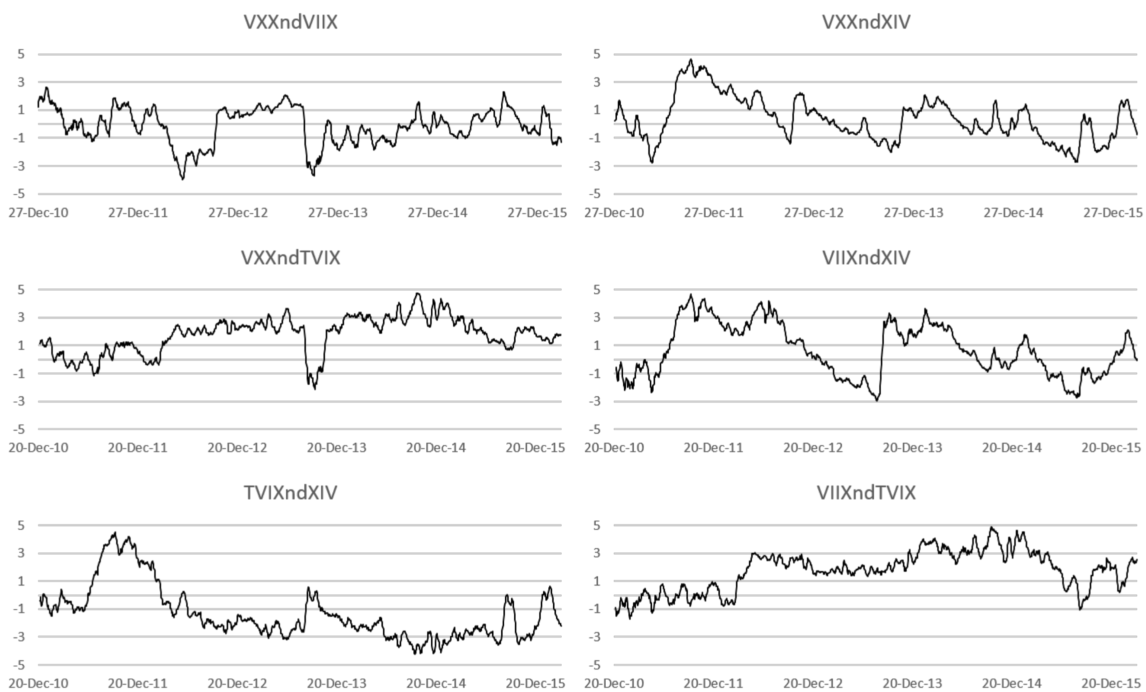

Figure 9: **Time variation in VIX futures ETN pair causality ratios: mid-term ETNs** This figure plots the 10-day moving average of the log Granger Causality ratio, as defined in equation (8), for the mid-term ETNs.