

Measuring the effectiveness of volatility auctions

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Abstract

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Keywords: Circuit breaker; trading halt, volatility auction; synthetic control; event studies; tracking portfolios

JEL Classification: C21, C58, G11, G14.

1. Introduction

Firm-specific trading halts are widely used in securities markets as a means of normalizing the trading process in times of excessive volatility. They belong to the group of circuit breakers that also includes price limits and market-wide trading halts (Kim and Yang 2004). Firm-specific trading halts are a common feature of stock exchanges around the world, such as the NYSE, NASDAQ, and Euronext, and those of Australia, Canada, Germany, Hong Kong, Israel, the UK, and Spain. However, there is no consensus on the need for or the effectiveness of trading halts. Moreover, interest in trading halts and price limits have rekindled in the aftermath of the Flash Crash in US futures and stock markets in May, 6, 2010 (Gomber, Lutat, Haferkorn, and Zimmermann 2011; Subrahmanyam, 2013; Dalko, 2016; Kirilenko, Kyle, Samadi and Tuzun, 2017) .

In principle, trading halts would be irrelevant in an efficient market because prices should respond immediately to the arrival of new information. However, market microstructure considerations might make them desirable. Specifically, trading halts have been justified as a way of mitigating the information disadvantage of uninformed traders or designated market makers, enabling the market to better accommodate large-volume shocks (Greenwald and Stein, 1988, 1991). Trading halts might also provide a “cooling off” period that supposedly allows investors to better process the incoming information (Kim, Yage and Yang, 2008). Theoretical models support this line of reasoning. Madhavan (1992), modeling a continuous market versus call auctions, finds that “the periodic auction aggregates information efficiently and is more robust to problems of information asymmetry in that it can operate where the continuous market fails” (p. 609). Spiegel and Subrahmanyam (2002) offer a model in which trading halts signal large information asymmetry affecting not only the halted stock, but also informationally related securities.

However, some academics oppose trading halts as undesired intrusions into a free market. Fama (1989) is against the “cooling off” period, arguing that any investors who want to cool off can do so by simply staying out of the market. Grossman (1990) states that investors, as “consenting adults”, should not be prevented from trading as they please. Grundy and McNichols (1989) propose a model of “learning through trading” that implies that in the absence of continuous trading potential traders are less able or willing to reveal their demands and information. Moreover, the theoretical analysis of Subrahmanyam (1994) finds that trading halts might have the perverse effect of exacerbating volatility because traders might sub-optimally advance their trades in anticipation.

We study the effect on market quality of a particular type of trading halt on the Colombian Stock Exchange (BVC): the rules-based volatility auction. As detailed below, volatility auctions on the BVC are trading halts triggered by the imminence of a trade outside price collars, switching continuous trading to a

short-lived call auction. Like those of the Spanish Stock Exchange (SIBE) after May 2001, trading halts on the BVC display two fundamental differences from those on the NYSE, NASDAQ, Montreal Exchange (MX), and Australian Stock Exchange (ASX). First, trading halts on the BVC are not subjectively imposed by a regulator, or requested by the firm in question, but rather are automatically activated by the trading system when the price of a forthcoming trade lies outside the established trading range. Second, trading is not completely halted, but rather switched to a short-lived call auction (lasting for 2–3 minutes), wherein investors can incorporate their preferences and information by posting limit orders. Thus, price discovery can still take place in an organized fashion.

This type of trading halt is also used in the Xetra trading system owned by the Deutsche Börse, where it goes under the name of “volatility interruptions.” These are regarded as a way of dealing with volatility spikes while allowing for smooth price discovery. In the words of the Deutsche Börse CEO, “*The auction concentrates liquidity, and the message that is sent to all market participants attracts further liquidity. This increase in liquidity in and of itself improves the price discovery process*” (Francioni, 2013 p. 27). They can also be found in the stock markets of Paris and Euronext (Reboredo, 2012).

Most of the previous literature have focused on information related trading halts. The evidence on their effectiveness in US markets is mixed. Motivated by the October 1987 crash, Lee, Ready, and Seguin (1994) report that trading halts on the NYSE are associated with subsequent increased trading activity and volatility. Christie, Corwin, and Harris (2002) study information dissemination in relation to NASDAQ trading halts of varying durations. They find increased volatility, volume, and bid–ask spreads after five-minute halts, but not after overnight halts. They interpret this as evidence of the importance of increased information transmission during the halt. Corwin and Lipson (2000), who also study NYSE trading halts, report increased trading activity and volatility and reduced liquidity after the halt. However, they also find two desirable consequences. First, traders take advantage of the halt to revise their trading intentions by cancelling and submitting orders. Second, the clearing price at which trading resumes after the halt is informative of the future price.

The evidence on information related trading halts from international markets is also mixed. Studying exchange-imposed halts, Kryzanowski and Nemiroff (1998) report increased volatility and volume on the MX. Frino, Lecce, and Segara (2011) find larger bid–ask spreads and reduced depth on the ASX. Studies focusing on the SIBE deal with two types of trading halts. Until May 2001, firm-specific trading halts were imposed by exchange officials when they were deemed necessary by price instability or incoming news, similar to the practice in the US. From May 2001 onwards, trading halts were replaced by rules-based volatility auctions triggered by prespecified price collars. Studying data relating to trading halts up to April

2001, Kim, Yage, and Yang (2008) find an overall beneficial effect: trading activity increases and the bid–ask spread is narrower, although volatility remains the same.

The evidence on volatility auctions is somewhat more favorable. Studying the SIBE volatility auctions, Reboredo (2012) finds improved price formation and a reduction in volatility, particularly for thinly traded stocks¹. Gomber, Lutat, Haferkorn, and Zimmermann (2011) study the effect of volatility auctions on the German Xetra stock market, as well as a satellite market, the London-based Chi-X MTF. They find a decline in stock volatility in both markets at the expense of increasing bid–ask spreads. However, market quality and price discovery in the satellite market decreases during the volatility auction. Zimmermann (2013), also focusing on the Xetra market, studies 1,800 volatility auctions using Corwin and Lipson’s (2000) methodology and finds that volatility auctions improve price discovery to a degree similar to that of the Xetra midday auctions. He also reports benefits in terms of market quality using the midday auctions as a control group, revealed in the form of a decrease in volatility and the proportional bid–ask spread following the volatility auction. However, recent evidence by Hautsch and Horvath (2019), using NASDAQ order book data and a natural experiment based on the introductions of such mechanism after May 2010, indicates that the auctions enhance price discovery during the halt but have adverse effects on price stability and liquidity afterwards.

More recently, there has been renewed interest in the usefulness of the trading halts, especially as a result of the incremental use of algorithmic trading and the possibility of malfunctioning trading systems. For example, the European Securities Market Authority has called for additional evidence regarding the effectiveness of the mechanism (European Commission, 2010). As mentioned by Zimmermann (2013), one important challenge has been setting up a framework to determine the causal relationship between the halt and the transaction price variability when the continuous market resumes afterwards². This seems to be an important drawback to most of the existing methodological approaches to measuring the effectiveness of trading halts, but, as discussed below, can be overcome by the methodology proposed in this study.

The contribution of this paper is twofold. First, to our knowledge this is the first paper to study the effect of volatility auctions on the market quality of an emerging market. The study of market microstructure design in emerging markets helps to better understand the price formation, volatility and liquidity in those venues and suggest alternatives in trading mechanisms and institutions design that improve it. Bekaert and

¹ Abad and Pascual (2010), also studying the SIBE, find increased volatility, volume, and information asymmetry, but acknowledge the lack of a proper counterfactual.

² Only the most recent papers use a causal inference approach. Hautsch and Horvath (2019) consider a natural experiment (comparison between a pre-regulation or post-regulation period) and a difference-in-difference methodology. Zimmermann (2013) compares volatility auctions and midday auctions.

Harvey (2002) remark the special challenges that market microstructure pose for emerging markets, emphasizing that many of those, at that time, were struggling about the right market design and institutions that improve price formation. Issues of thin trading, excessive volatility, and insider trading are pervasive in emerging stock markets, occasionally leading to market failure and limiting their development over time. Those problems are likely to be compounded in a small emerging market such as Colombia. Since trading halts have been justified as a way to reduce information asymmetry, protect uninformed investors, and mitigate excessive volatility, a stock market such as the BVC is an ideal case study.

Second, this paper presents a methodological contribution to the study of market microstructure events. We use a synthetic portfolio as a contemporaneous counterfactual for the stock affected by the volatility auction. As described in Section 3, we estimate this in a pre-event period, as the portfolio of stocks not involved in a trading halt. Thus, we compare the change in the variable of interest (volatility, spreads, or trading activity) for the halted stock, following the event, with the change in the same variable for the synthetic portfolio. The synthetic portfolio methodology is adapted from existing methods for causal inference in applied microeconomics (Abadie, Diamond and Hainmuller, 2010), but to the best of our knowledge it has not been used in intraday market event studies³. These quasi-experimental methods are starting to attract interest in finance and accounting research (Gow, Larcker and Reiss, 2016). The main reason is that although finance and accounting research addresses questions that are causal in nature, the methodologies that have been used for a long time, such as event studies, have yet to include methodological advances in causal inference that have been developed in other disciplines.

Stock matching is the most widely used approach in these types of studies. For example, Jian, McInish, and Upson (2009) study firm-specific trading halts on the NYSE, pairing each halted stock with an informationally related stock in the same four-digit SIC industry, and with close correlation of returns, volume, volatility, and adverse selection component of the spread. However, this methodology is clearly unsuitable for a small stock market. Further, the pseudo-matching methodology of Lee, Ready, and Seguin (1994) pairs the period of the trading halt with a different trading period for the same stock. However, this approach omits any systematic effect on market quality variables around the trading halt. We suggest that the methodology proposed here can overcome the limitations of these approaches, particularly in the context of a small stock market, by taking advantage of the availability of high-frequency data and new research design methods. The two studies most closely related to the present one are those of Gomber et al. (2011) and Zimmerman (2013) on the German Xetra stock market. However, our study differs not only in relation

³ There is a recent application of synthetic matching with daily data, Acemoglu, Johnson, Kermani and Kwak (2016).

to the sample data, but also in terms of the methodological approach. Zimmermann (2013) does not use stock matching, and Gomber et al. (2011) match the same stock at different times (midday auction).

Our main hypothesis is that volatility auctions, as intended, effectively reduce volatility. That is, volatility diminishes after the continuous market resumes compared with what it would have been if no auction had taken place. The reasoning is that in the call auction, orders are batched together and there is simultaneous execution at a single equilibrium price at the closing, which enables a better price discovery process than in the continuous market. The more informative price mitigates the need for subsequent price adjustments and in doing so avoids excessive volatility in the market. This has been an important argument in favor of using call auctions to open and close continuous markets (Pagano, Peng and Schwartz, 2013) ⁴.

In a different facet of market quality, volatility auctions should improve subsequent liquidity (e.g. lower bid–ask spreads) by mitigating asymmetric information, according to the theoretical model of Madhavan (1995). Further, to the extent that volatility auctions increase the visibility of the stock, they might also increase the proportion of uninformed traders, leading to improved liquidity and increased trading activity in the subsequent continuous market, in line with classical informed trading models such as Kyle (1985) and Glosten and Milgrom (1985). Supporting results have been found by Zimmermann (2013) in the German Xetra stock market ⁵.

Our findings can be summarized as follows. The volatility auction has a statistically and quantitatively significant effect on attenuating price uncertainty once continuous trading recommences. In the absence of the call auction, the volatility of the affected stock, as proxied by the synthetic portfolio, would have been significantly higher. Conversely, using the weights estimated from the synthetic portfolio, we find no

⁴ However, as noted above, some empirical evidence suggests that, at least some trading halt mechanisms are themselves a source of volatility (Kryzanowski and Nemiroff, 1998; Christie, Corwin and Harris, 2002; Kim, Yage and Yang, 2008; Abad and Pascual, 2010).

⁵ Alternatively, trading halts might impair liquidity, as reported by Gomber, Lutat, Haferkorn, and Zimmermann (2011) in relation to the Xetra stock market and Abad and Pascual (2010) in relation to the SIBE. This can be explained in two ways. First, according to the “learning through trading” models cited by Lee et al. (1994), the absence of trading prices during the halt (with or without call auctions) might discourage potential traders from revealing their demands. Second, liquidity can decrease if the call auction does not last long enough for proper information dissemination prior to the reopening of the continuous market, as empirically tested by Christie et al. (2002).

evidence that the auction has a significant effect on other dimensions of market quality such as liquidity, depth, or trading activity. Overall, the synthetic portfolio provides a simple yet accurate strategy to proxy the behavior of the asset had the auction not taken place. Furthermore, the volatility auction on the BVC, a type of rules-based circuit breaker, seems to have the desired effect, which is to reduce volatility without affecting other measures of market quality.

The rest of the paper is organized as follows. Section 2 discusses the relevant institutional features of the BVC. Section 3 presents the data and explains the sample selection. Section 4 presents the synthetic portfolio method and compares it to traditional event study approaches within the framework of causal inference methods. Section 5 discusses the empirical results of the intraday event studies. Section 6 concludes.

2. Volatility auction

In February 2009, the BVC launched a new electronic stock trading platform incorporating features such as volatility auctions (AUTHOR 2014). The purpose of these rules-based market interruptions is to give investors an opportunity to receive and react to market information, to form a price in an orderly manner, and hence to mitigate excess volatility. Specifically, a volatility auction for a stock is triggered at any time during the continuous market by an order that would lead to a transaction outside a predetermined price range. The price range is set around the closing price of the previous day, with a bandwidth in one of three sizes (6.5%, 5.5%, and 4%). The bandwidth is determined quarterly as a function of the past volatility of the stock (Figure 1).

[Insert Figure 1]

As soon as the auction begins, outstanding orders are withdrawn from the book, except for the one that triggered the auction. The duration of the auction is on average two and a half minutes, with a 30-second period where the auction closes randomly. When the auction ends, the equilibrium price is calculated as that which maximizes trading volume. The price range is then recalculated around the equilibrium price. There is no maximum number of volatility auctions, and a new auction for the same stock can start as soon as another auction ends.

3. Data and sample selection

We use trade and quote (TAQ) data for 41 listed stocks on the BVC from August 2010 to August 2012. We obtain the TAQ data from Bloomberg Professional online subscription service. The data contain bid and ask quotes, trades, and volumes. From a private database of BVC we obtain time stamps signifying the beginning and end of volatility auctions on specific stocks. These can start at any time during the trading day, and there is no particular time of day when most auctions take place (see Figure 2a). In total, there are 1062 volatility auctions, about 90% of which are concentrated on 19 stocks.

[Insert Figure 2]

We start by defining the asset space in the market, which comprises a total of J securities that are sufficiently liquid to be traded continuously throughout the day (S_1, S_2, \dots, S_J). We identify the time and day of the volatility auction affecting security S_j , and without loss of generality we define $j = 1$. This means that trading for security 1 has been switched to a volatility auction. During the same period, there is a set of other securities $\mathcal{S} = (S_2, \dots, S_J)$ still traded in a continuous market.

We define sample selection criteria to avoid confounding effects from different sources that can lead to a biased measure and to ensure enough information available from a trading day to test our hypotheses. We apply the following criteria to determine whether the auction for security 1 is retained in the selected sample: a) we discard auctions that take place near the closing of the day to avoid interference of the closing auction; b) discard consecutive volatility auctions affecting the same security S_1 within the same day⁶; c) verify that security 1 has sufficient trading activity during the day. In addition, we must ensure that securities in the control group, \mathcal{S} , have sufficient trading activity during the day, and that none of those securities are affected by a volatility auction on the same day⁷.

Applying these selection criteria to the transaction (quote) data, the number of auctions in the sample falls to 184 (441), i.e. 17% (42%), of the original sample of 1062 auctions.

⁶ There are only a few cases (7) of consecutive volatility auctions on the same stock.

⁷ Since volatility auctions take place at different times of the day we do not have a standardized measure of the number the window size before and after the auction when we use the intraday information through-out the day. This implies that the time after the auction can vary from 40 minutes and up to 6 hours, with an average value of 3.5 hours. We complement these results with an exercise where we fix time window to one hour before and after the auction.

Even though a significant number of observations is lost through this sample selection procedure, the reduced sample is still representative of the auctions taking place at different times of the trading day (see Figure 2b). We perform the analyses to test our hypotheses using trade data and quote data separately. For example, we measure volatility from returns using transaction price or mid-price data.

The volatility auction mechanism is designed to address strong price movements in a particular stock rather than market wide effects. However, it's important to determine if such interruption occurs simultaneously across stocks. To verify the possible existence of multiple auctions across different stocks occurring at approximately the same time, we count the number of auctions that occurred within a time interval in the full sample (1062 volatility auctions). Figure 3 provides the distribution of the number of volatility auctions that occur within a day, within 1 hour or 30, 10, 5 and 1 minute. We expect that the number of auctions will be fewer as the time interval is smaller. At the day frequency, there are some outliers, for example, 28 volatility auctions affect the same number of stocks in one day, but the median is about two auctions per trading day. For a time interval of under 1 hour, we observe that there is only one volatility auction per interval with very few exceptions that we exclude using our sample selection criteria.

[Insert Figure 3]

We provide an initial assessment of the impact of volatility auctions on market quality by analyzing changes before and after for the variables of interest (volatility, liquidity and trading activity) in the cross section of available auctions. Table 1 presents the medians of the variables of interest for the stock affected by the auction (treated), the average effect on the stocks that make-up the control group and the market⁸. In the third column, we test the significance of the difference between the measures before and after the auction⁹. With respect to volatility, there is a significant change after the auction but we obtain mixed results, measured with trades volatility actually increases, whereas with mid-prices the mechanism seems to be performing, as it should. The change in the controls is non-existent and in the market, it is at best very small. With respect to the other market quality variables (liquidity and trading activity), we find no significant change around the auction. The last panel in the table summarizes the results of individual tests performed on each of the auctions. We perform robust two-sample test based on the difference or the ratio

⁸ The market is represented by the intraday value of the COLCAP, the main index of BVC.

⁹ As a standard practice in event studies, we introduce a gap between the time of the event and the estimation window and the post-event window. Specifically we ignore the data in intervals of five minutes around of the start and the end of the auction.

between the measures before and after the auction. The percentages indicate the number of auctions where we reject the null hypothesis that the measures are statistically equivalent using the sample data before and after the auction. A higher percentage indicated that there are more auctions where the variables of interest change around the auction. The percentage tends to be higher in the treated variable than in the control or the overall market.

[Insert Table 1]

4. Methodology.

a. The synthetic portfolio method

In traditional event studies (MacKinlay, 1997), the effect of a particular event on a stocks's price is measured by the abnormal returns (ARs). For simplicity, suppose that stock 1 is the only security affected by an event, the abnormal return is:

$$AR_{1,t} = R_{1,t} - E[R_{1,t} | X_t], \quad t \in (T_0, T] \quad (1)$$

where $R_{1,t}$ is the actual return and $E[R_{1,t} | X_t]$ is the expected normal return. There are two common choices for modeling the expected return: the constant mean return model and the market model. In both cases researchers use information in the pre-event window to quantify the normal return. In the constant mean return model, the normal return is the simple average of the variable of interest in the pre-event window. In the market model, the normal return is given by, $E[R_{1,t} | X_t] = \hat{\alpha}_1 + \hat{\beta}_1 R_{m,t}$, where $R_{m,t}$ is the excess market return at time t and $\hat{\beta}$ is the estimated slope in the following regression, estimated with data in the pre-event window.

$$R_{1,t} = \alpha_1 + \beta_1 R_{m,t} + \epsilon_{1,t}. \quad (2)$$

For the event study we perform on volatility auctions, we follow an approach that deviates from the use of the market model or the constant mean model to build the expected normal return. We adapt existing methods in causal inference, in particular, synthetic control methods (introduced by Abadie, Diamond and Hainmuller, 2010) in order to build a counterfactual for the expected normal return; that is we obtain an estimate of the returns of stock 1 in the absence of the volatility auction using a linear combination of the returns of the stocks in the control group¹⁰.

¹⁰ The synthetic control method (Abadie, Diamond and Hainmuller, 2010), has received a lot of attention in

Synthetic matching techniques applied for event studies in finance are not common, we are only aware of their application in a recent paper, Acemoglu, Johnson, Kermani and Kwak (2016). In this paper, the authors measure the effect of personal connections on the returns of financial firms. The study is based on the connections of Timothy Geithner to different financial institutions prior to his nomination as Treasury Secretary at the end of 2008. The authors use a synthetic matching methodology to complement to the usual approach in event studies of capturing the difference between a treatment and control group using for the latter the fitted market model.

We illustrate the synthetic matching methodology using an event study methodology with a synthetic portfolio as measure of the expected normal returns. The event of interest is the volatility auction, and our purpose is to determine the causal effect of such a market mechanism on market quality variables after continuous trading is resumed.

We denote t as the intraday time ($1 < t < T$) and T_0 as the time when the auction takes place. Although, the auction lasts for approximately two and a half minutes, for notational simplicity we denote this interval as a particular moment in time, T_0 . The pre-event or estimation window is defined by $t \in [1, T_0)$, and the post-event or forecast window is defined by $t \in [T_0, T)$. The main challenge in determining the causal effect of the volatility auction (the intervention) on a given stock is the construction of a potential outcome or counterfactual. This tries to capture what would have happened to the stock return had the volatility auction not taken place.

The available data is intra-day data (sampled every 5 minutes) of the securities of interest $Y_{j,t}$ for stock $j = 1, \dots, J$ and, $t = 1, \dots, T$ where $T_0 < T$. Suppose that stock 1 is the only one affected by the intervention, that is $Y_{1,t}$ receives the treatment and the rest of the stock ($Y_{2,t}, \dots, Y_{J,t}$) are in the control group. Let $Y_{j,t}^N$ ($Y_{j,t}^I$) denote the outcome that would be (is) observed for stock j if the volatility auction had not taken (takes) place at time, T_0 . Note that $Y_{j,t}^N$ is a latent variable and $Y_{j,t}^I$ is the observed outcome for the variable of interest after the intervention ($T_0 < t < T$).

comparative case studies on different subjects: terrorism, natural disasters, and tobacco control programs. As opposed to competing methods, synthetic control method's strength relies in the use of a combination of units to build a more objective comparison for the unit exposed to the intervention, rather than a choosing a single unit or an Ad hoc reference group. The authors advocate for the use of data driven procedures to build the reference group. The synthetic control method is a weighted average of the available control units, which makes explicit: the contribution of each unit to the counterfactual of interest and the similarities (or lack thereof) between the units affected by the event or the intervention of interest and the synthetic control in terms of the pre-intervention outcomes and other predictors of post-intervention outcomes.

In our application and similar to traditional event studies, the variable of interest is stock returns ($Y_{j,t} := R_{j,t}$). Therefore, $R_{1,t}$ is the return of the stock whose trading has been halted because of the volatility auction (the stock that has been treated). Conversely, the synthetic portfolio is built using the other securities (those in continuous trading before and after the intervention) to replicate the performance of the security of interest.

The methodology is very simple because we only need to obtain the portfolio weights w_j^* by solving the following optimal tracking problem, for the estimation window $\in [1, T_0)$.

$$w^* = \underset{w}{\operatorname{argmin}} \sum_{t=1}^{T_0} \left(R_{1,t} - \sum_{j=2}^J w_j R_{j,t} \right)^2, \quad (5)$$

The optimization is constrained because weights must sum to one ($\sum_{j=2}^J w_j = 1$). It is possible to include in this optimization problem additional restrictions on the estimated weights, for example non-negativity constraints¹¹.

A proper tracking of the stock of interest would guarantee that the synthetic portfolio provides a potential outcome for the latent variable $R_{1,t}^N$ in the post event window $(T_0, T]$ ¹².

The effect of the intervention is equivalent to the abnormal returns of the asset of interest,

$$\hat{\alpha}_{1,t} = AR_{1,t} = R_{1,t} - R_{1,t}^N = R_{1,t} - \sum_{j=2}^J w_j^* R_{j,t}, \quad t \in (T_0, T]. \quad (6)$$

As indicated previously, traditional financial event studies provide two approaches to quantify the latent return $R_{1,t}^N$ usually denoted as the expected normal return. The intent is to capture the usual behavior or the return in the absence of the intervention; the approaches are the constant mean return model or the market model. It is possible to think of both approaches in a more general framework. The first approach only considers lagged time-series information from the stock on the return of interest in the estimation window $(R_{1,1}, \dots, R_{1,T_0-1})$ to estimate, $R_{1,t}^N$. Lagged time series information with equal weights assigned to all observations is the usual approach known as the constant mean return model. It is also possible to use a different weighting to come up with a different version of the estimate for $R_{1,t}^N$; for example it would be

¹¹ Later we compare the performance of the restricted (non-negative weights) and the unrestricted weights.

¹² The goodness of fit of the matching is determined by estimating the Mean Square Error in the estimation window or by testing that the cumulative abnormal returns are not statistically different from zero.

quite natural to assume that return follow a stationary AR(1) process and use the estimated coefficients (the first autocorrelation) to obtain the desired estimate of the potential outcome¹³. The more popular approach is to use the market model or some other factor model (Fama-French three-factor or Carhart four factor model). This is actually very close to the original idea of a synthetic control (Abadie, et al. 2010), where the data generating process of $R_{1,t}^N$ is determined by a factor model¹⁴. In finance factor models are used in many applications, and although there is an extensive literature, there is also an important discussion on the validity of the factors used to explain the cross section of returns (Harvey, Liu and Zhu, 2015).

The synthetic matching or synthetic portfolio approach can be considered an alternative way of defining an expected normal return model, which avoids strong assumptions on the effects of treatment or non-treatment. The synthetic portfolio method is very general, and does not require a natural experiment or *ad hoc* criteria to select the securities in the control group; therefore, researchers can use it in many types of event studies. One advantage of synthetic matching over traditional methods is the use of a different set of securities than the security of interest, the treated observation, which avoids any interference of the event on the potential outcome of interest. Under perfect circumstances, there is a well-defined control group. Off course, one must take care in avoiding any hidden variation that might spill over from the event to the control group¹⁵. There are of course other approaches for causal inference that could be explored as an alternative, for example matching score methods such as propensity score, a method that is already popular in empirical finance. We do not use propensity score because the matching is based on a set of exogenous covariates hence we have to define a model that selects a particular set of covariates that are significant to determine treatment, this of course creates model risk and arbitrariness from the point of view of the researcher; however it might enhance the matching by including information beyond the pre-treatment outcome variables that we use¹⁶. Our proposal of the synthetic portfolio method is mainly based on the methodological resembles to traditional event study methods that we have mentioned before. We leave the

¹³ The AR(1) process can be justified on the basis of the effects of the bid-ask spread bounce on the price process, (Roll 1984).

¹⁴ Abadie et al. (2010) treat the potential outcome problem as a missing data one and therefore define a data generating process for the missing outcome. The choice is a factor model that includes observed covariates and unobserved components. Both elements are unit specific (for each stock) and are not time varying. The implementation of synthetic control methods for the present case is not straightforward because there are no unit specific controls relevant for the sampling frequency.

¹⁵ One could argue that the market model does also provide a way to avoid the used of the treated variable in the construction of the potential outcome; this is true because one would expect that in a liquid and deep market the security of interest is only one of many constituents of the index. This is however not necessarily true for thinly traded markets where the index can be determined mostly by a handful of assets. For example, by early August 2010, four stocks of the twenty that constitute the COLCAP made up 56% of the index value.

¹⁶ This implies a trade-off between a model with tighter restriction on the matching of units with the use of covariates and a miss specification problem brought on by the model or the wrong covariates.

relationship and the comparison of the relative performance of synthetic portfolio and propensity score for these types of events studies as an open methodological question.

[Insert Figure 4]

Figure 4 provides a graphical illustration of how synthetic portfolio method works. The continuous line shows the observed evolution of returns for security 1 before and after the event, while the dash line shows the evolution of the synthetic portfolio. Note that in the pre-event window, the synthetic portfolio performs well in tracking the performance of security 1, as it clearly replicates the return on the security of interest¹⁷. Thus, we have a strong proxy for security 1 just before the volatility auction. Once the volatility auction is complete and a new equilibrium price is obtained, continuous trading resumes in the post-event window and we see the evolution of the returns on security 1 that have been affected or treated by the volatility auction. Thus, the post-event return on the synthetic portfolio $R_{1,t}^N := \sum_{j=2}^J w_j^* R_{j,t}$ becomes a proxy for the unobserved potential outcome in relation to security 1, had the volatility auction not taken place, in other words the state in which security 1 is not exposed to the volatility auction (the treatment). We emphasize that none of the securities in the synthetic portfolio are affected by the volatility auction, and thus have received no treatment. It is important to note the effects of the sample selection criteria over the estimated effect of the intervention. That is, the effect of the sample selection criteria that we impose on the elements of the control group regarding the no inclusion of stocks that have a similar type of volatility auction over the trading day. The main reason to include this criterion is to avoid any interference in the measure by using a very strict condition on being part of the control group. However, this creates a censoring of the potential outcome because these stocks never have price paths that excess the limits defined by the mechanism. This implies that by censoring the potential outcome (the synthetic portfolio) we measure a lower bound for the effect with respect to the non-censored case. Therefore, the effect of the intervention measured in terms of the abnormal returns of stock 1 ($AR_{1,t}$) is a conservative lower bound for the true uncensored effect.

b. Measuring the causal effects of volatility auctions.

In order to map returns to volatility of stock 1 (treated) and the synthetic portfolio in the pre-event and post-event window we obtain five-minute realized volatility (Liu et al. 2015). To perform inference on the

¹⁷ It is possible to use several test to evaluate tracking performance in the estimation window, for example using the root mean square error or a test of hypothesis on the tracking error, which is actually equivalent to testing the cumulative abnormal returns. The null hypothesis of the test would be that the tracking error or the cumulative abnormal returns are equal to zero.

estimated realized volatilities before and after the auction we use a nonparametric two-sample scale test. These tests provide: first, a measure of tracking performance in the estimation window with respect to the variable of interest and that the estimated volatilities are equivalent (two-sided test), and; second, a method to determine if the volatility auction mechanism is working, hence the volatility of the non-treated (the synthetic portfolio) is significantly larger than the treated unit (stock 1), for this we use a one-sided test. We also follow the suggestion of Abadie, et al. (2010) and form a placebo test for the synthetic matching. The purpose of the placebo test is to randomize treatment within the units of analysis (stock 1 and the stocks in the control group) that are trading at the same time. This exercise allows us to determine whether the estimated effect of the volatility auction (on stock 1) is large relative to the distribution of the effects estimated on for the stocks in the control group that are not exposed to the interruption. We perform these last tests in the post-event window.

We use the weights of the synthetic portfolio, to build synthetic indicators of the other variables of interest (bid–ask spreads, depth, and turnover). We can generalize the previous measure of abnormal returns to a measure of the effects of a volatility auction on any of the variables that are informative with respect to market quality:

$$\begin{aligned}\delta_{1,t} &= Y_{1,t} - Y_{P,t} \\ &= Y_{1,t} - \sum_{j=2}^J w_j^* Y_{j,t} \quad t \in (T_0, T]. \quad (4)\end{aligned}$$

Since most of the indicators of market quality have a strictly positive support, we use weights of the synthetic portfolio returns based on the restricted estimator (weights are non-negative, $w_j^* \geq 0$). We do not perform a separate matching procedure for each variable, because we do not have a large number of assets in the control group and hence imposing non-negativity constraint on the weights usually leads to selecting one of the stocks. When the methodology only select one of the stocks, the tracking performance is very poor and hence we rather use the weights obtained from tracking returns.

We also perform hypothesis test on the pre-event and post-event outcomes of the other variables of interest (bid–ask spread, turnover). For all of the variables and the results that we present in the following sections we only use volatility auctions where there is good tracking performance in the estimation window.

5 Empirical analysis

5.1 The synthetic portfolio

For each of the auctions, our empirical strategy requires us to build a synthetic portfolio that provides an accurate tracking performance of the asset of interest before the auction. We then use this portfolio to trace the potential outcome (in the post-event window) for the same asset had the auction not taken place.

We illustrate the method by selecting two auctions (see Figure 5). The first auction took place on 16 November, 2010 at 11:50:39, and related to the stock of an oil and gas company (ticker: ECOPETL). The second auction took place on 9 August, 2011 at 12:25:43, and related to the stock of a commercial bank (ticker: PFBCOLO). In both cases, the top panel shows how the restricted (dashed line) and the unrestricted synthetic portfolio (dotted line) is able to track the five-minute returns of the stock during the estimation window. The vertical line indicates the beginning and end of the auction¹⁸. After the auction has ended, the post-event window shows the deviation between the observed returns (the treated case) of the asset and the returns of the synthetic portfolio acting as the potential outcome (non-treated case). In the post-event window, the variation between the returns of the synthetic portfolio and the observed returns in both stocks is expected to be significant because the counterfactual is designed to capture an unobserved state wherein the auction did not take place.

[Insert Figure 5]

One advantage of using intraday data is that, compared with daily data, there is less chance of introducing confounding effects unrelated to the volatility auction. Furthermore, the construction of the counterfactual using a synthetic portfolio is more robust. Compared with other approaches used in comparative case studies, we are not choosing one particular asset or reference group of assets to build the counterfactual, but rather we are using an optimal set of weights to replicate the asset of interest using a control group that has not been affected by the auction. Although there are bound to be some externalities from informationally related securities, as identified by Jian, McNish, and Upson (2009), our approach is a less biased alternative because the weights are estimated rather than imposed. The bottom panels in Figure 5 show the estimated weights that are used to build the synthetic portfolio in the two auctions, for both the

¹⁸ The information provided during the auction is not considered in the pre- or post-event windows, we also use a 5-minute gap before the auction starts and after the auction ends.

restricted ($w \geq 0$) and the unrestricted case (w free). Each asset in the control group receives a positive or negative weight. The asset does not necessarily belong to a specific asset class that has similar characteristics to the asset affected by the auction. For example, in some comparative case studies, Guidolin and La Ferrara (2007), the authors build the control group by choosing companies in the same sector. The synthetic portfolio is only built on the notion that a particular asset in the control group (not treated by the volatility auction) provides a contribution to tracking the asset of interest (the stock that will be affected by the volatility auction) before the realization of the event of interest (the volatility auction).

In table 2, we look at the performance of synthetic portfolio in both the estimation as well as the post-event window. In the top left panel we compare the performance of the synthetic portfolio method against the traditional event study methods (time series or market model approach) using the root mean square error (RMSE) between the observed and the estimated returns along the estimation window. We find that the synthetic portfolio does not provide a better alternative when trying to fit the returns of the asset of interest, all the more when using unrestricted weights. However, we are not interested in testing cumulative abnormal returns, which is equivalent to looking at the RMSE, rather we are interested in testing the difference between the volatilities of the treated unit and the synthetic portfolio in the estimation window. Good tracking performance will guarantee a replication of the volatility by the synthetic portfolio with respect to the treated unit. In the top right panel, we provide the percentage of auctions where we can reject the null hypothesis that the volatilities are different between the volatility of the treated and the non-treated. The results indicate a slight advantage of synthetic control methods (less rejections) for the same set of auctions.

In the two lower panels of Table 2, we look at the performance of synthetic portfolio in the post-event window. We use the placebo test proposed by Abadie et al. (2010) to look at the robustness of the results. The idea is that the estimated effect of non-treatment, in this case no auction, the volatility is larger in magnitude than in the case where there is a randomized treatment over the control units and the treatment unit (including it in the portfolio). The results indicate the percentage of auctions where the volatility of the synthetic after the auction is above the 95th percentile of the placebo distribution. If this is so then the magnitude of the effect is well above the randomization of the treatments over all units. The percentage of auctions that overcome the placebo test is 36 to 42% of the auctions analyzed. Imposing non-negativity constraints in the weights creates a significant reduction in auctions that pass the placebo-test and hence we concentrate on the results for the unrestricted case but making sure that the matching is adequate for volatility in the estimation window.

[Insert Table 2]

5.2 Impact of volatility auctions on volatility

To assess the impact of the volatility auction on volatility, following the methodology outlined in the previous section, we estimate five-minute realized volatilities for the treated stock and for the non-treated control (the synthetic portfolio) both before and after the auction. We are only using auctions where the synthetic portfolio has a good tracking performance of the asset of interest in the pre-event window. If our main hypothesis is correct and the volatility auction avoids large price variations, the asset that has gone into the auction (treated) displays lower volatility than the potential outcome captured by the synthetic (non-treated) portfolio, after the auction. In figure 6, we capture the average effect using the cross section of volatilities for the auctions. There are two panels in every subfigure. The left panel is a scatter plot of the treated and non-treated units before the auction. A black dashed line represents the case where the volatility of the non-treated is exactly equal to the volatility of the treated (45° degree line). In other words, the line has a zero intercept and a slope exactly equal to one. The blue solid line represents the estimated OLS fitting line and the gray area the corresponding 95th confidence interval. A perfect matching before the auction would require that the solid line coincides with the dashed line on that the intercept and the slope of the estimated solid is statistically equal to zero and one, respectively. This is not the case in any of the right panels, but in general the matching is close enough and the dashed line is within the gray area (except in subfigure b). This is the best match we can accomplish given that we are already using the subset of auctions where we cannot reject the null hypothesis that the estimated realized volatilities are equivalent before the auction (in the left panel of each subfigure).

In the right panel of each subfigure, we use the same auctions and present the observed volatility of the treated unit after the auction and the volatility of the synthetic portfolio using the estimated weights and the observed return process for the stocks belonging to the control group (no treatment). This is our estimate of what would have happened to the volatility had the auction not taken place. The estimated line based on these set of points will give us a rough estimate of the average effect of the volatility auction mechanism. In particular, we look at the difference between the intercept of both blue solid curves before and after the auction as the measure of the effect of the volatility auction. In other words the intercept captures the average effect on the non-treated before (observed volatility of the stock before the auction) and after the auction (volatility of the synthetic portfolio). The results indicate between 3% and 6% less volatility in the stocks subject to volatility auctions, in other words this is 10 to 25 times larger than what we see in the average data before and after the auction (Table 1).

Alternatively, in Table 3 we look at the difference in the medians and perform a two-sample Wilcoxon test on the data points for the treated and non-treated units. The average effect of the volatility auction (the difference between the treated and the non-treated) is between 1.2% and 8% less volatility after trading resumes (first column of Table 3). Using the data just one hour before and after the auction the effect is between 2.2% and 4%.

[Insert Figure 6]

Looking at the plots in Figure 6, the top and bottom panels differ in terms of the information used to estimate the returns and volatilities, i.e. transaction prices versus mid-prices. The right and left panels differ in terms of the amount of five-minute returns used to estimate the realized volatilities. In the left panels, all of the information in both the pre- and post-event windows is used¹⁹. In the right panels, we only consider five-minute returns for one hour before and after the auction. In all of the four panels of Figure 6, we observe that the volatility auction delivers a relative reduction in volatility, which is in line with the results for the German Xetra stock market (Gombet et al., 2011; Zimmerman, 2013) and Spanish stock market (Reboredo, 2010)²⁰.

From the results of table 3, in general we find that the volatility of the treated stock after the auction does not change whereas the volatility of the non-treated always increases and the increase is statistically significant. Only in one case, volatility based on trades using all available data, we find that the volatility is increasing in both the treated and the non-treated synthetic, but the last one in a greater amount (more than twice). Because we are not exploring the specific causes of the increase in volatility that triggered the auction, our conclusions on the performance of the volatility auction mechanism assume that it mitigates volatility spikes in individual stocks (by a reduction or bounding) and not in the overall market. The additional evidence presented in figure 3 regarding the low occurrence of multiple auctions does not indicate that the auctions are triggered by systemic effects in the market. However, it's still plausible that a

¹⁹ Note that the amount of available information can differ because it depends on the time when the auction takes place during the trading day.

²⁰ We performed robustness tests based on one-minute and 10-minute returns and the results were equivalent with respect to the effectiveness of the mechanism, the only significant difference being that in some cases we had a smaller number of feasible auctions to analyze, and thus tracking performance declined at these frequencies. These results are available upon request to the authors.

peak in the market volatility will only affect one stock with a combination of high beta and high idiosyncratic volatility relative to the predefined price range²¹.

[Insert Table 3]

5.3 Impact of volatility auctions on liquidity

Similar to volatility, we measure the effect of volatility auctions on other variables of market quality for both treated stocks and the corresponding synthetic portfolios. Figure 7 shows the change in the bid–ask spread for the two groups. The top graphs show the results for the effective bid–ask spread, while the bottom graphs show the results for the quoted bid–ask spread, both of which are defined in Goyenko, Holden, and Trzcinka (2009). As before, the left panels use all the available information on the trading day, while the right panels only use information from one hour before and after the call auction. It is apparent that the volatility auction does not have a significant effect on the bid–ask spread for the treated stock, as the circles are reasonably evenly distributed above and below the black line in all four cases. Interestingly, the liquidity measure seems to decrease after the call auction for the non-treated group, as the circles tend to be below the black line in all four panels. These preliminary results clearly refute the hypothesis that volatility auctions improve the liquidity of the treated stocks.

[Insert Figure 7]

Table 3 also includes the median of the measures of liquidity and trading activity for both groups, before and after the auction. We include five liquidity measures: the quoted and effective spreads, the depths at both quotes, and the ratio of the bid–ask spread to average depth, as presented by Jiang et al. (2009). Focusing on the results with all of the available data (columns 1 and 2), there is a reduction in the quoted bid–ask spread in both groups, significant at the 5% level, and also in the spread/depth ratio. Moreover, there is a statistically significant reduction in the effective bid–ask spread in the control group, but not in the treated stock. This minor increase in liquidity in both the stock and the synthetic portfolio can be

²¹ The difficulty lies in the fact that in order to disentangle systemic and idiosyncratic volatility we have to make strong assumption in the data generating process and in particular the effect on the potential outcome. This is however contrary to our initial motivation of making few assumptions as possible to arrive at an estimate of the potential outcome.

attributed to the well-known trend whereby liquidity improves during the trading day. In turn, there is a significant drop on the bid depth of the treated stock, but the opposite effect for the synthetic portfolio. In terms of trading activity, measured by the turnover, there is no significant effect on either the stock undergoing the auction (treated) or the synthetic portfolio (non-treated). Overall, the results in Table 3 indicate that the volatility auction does not have a discernible effect on the market quality variables of the treated stock other than volatility itself.

6 Conclusions

In this paper, we investigate the effectiveness of a type of circuit breaker known as volatility auction in an emerging market. In doing this, we address one of the main difficulties in event studies: building a credible counterfactual. Traditionally, similar studies have used different alternatives of the counterfactual: one based on the market model, a group of similar assets, or pseudo-events. We suggest a different methodological approach by proposing a synthetic portfolio for event studies. This approach allows us to build a more general and robust counterfactual. Ours is the best tracking portfolio for the stock of interest, obtained as a weighted average of the returns on the stocks that have not been affected by the event. The methodology has enormous potential for overcoming some common problems in event studies, such as confounding effects, and the difficulty of finding enough valid stocks to build a control group in small stock markets.

We use the synthetic portfolio method to test whether the volatility auction implemented in the Colombian Stock Exchange (BVC) is fulfilling its intended purpose. Specifically, we study volatility auctions observed over a two-year period from 2010 to 2012, using a proprietary volatility auction database from BVC and TAQ data from Bloomberg. We find this mechanism effective on mitigating excessive volatility during the trading day. In addition, we find no discernible effect on other dimensions of market quality such as liquidity measures, and trading activity. At least in BVC, the trade-off imposed by volatility auctions of reduced ability to trade on the one side, to gain a more orderly trading and volatility mitigation, is clearly desirable.

In terms of practical implications, the results of this study lend support to the use of volatility auctions, particularly in small emerging markets. Excessive trading volatility can be tamed to some extent by this type of mechanism, without affecting other variables of market quality. By allowing a cool-off period and

pooling together buyers and sellers in the call auction, this mechanism allows forming an equilibrium price that better incorporates the standing information. Volatility auctions also reduce asymmetric information for the liquidity providers, a very desirable feature in most emerging markets where liquidity is voluntarily provided by the participants, not supplied by authorized dealers or designated market makers. Still, there are some details to be further studied. Most importantly, future work should explore the effect of the width of the price collar that triggers the volatility auction on the volatility and other variables of market quality.

On the other hand, there are some obstacles to overcome applying the synthetic portfolio methodology in event studies. For example, we do not explore the role of covariates, widely accepted as critical for matching in causal inference. One possibility for future work is to use parametric portfolio policies to introduce covariates in the weights of optimized portfolios and explore the benefit of such choices in the methodology.

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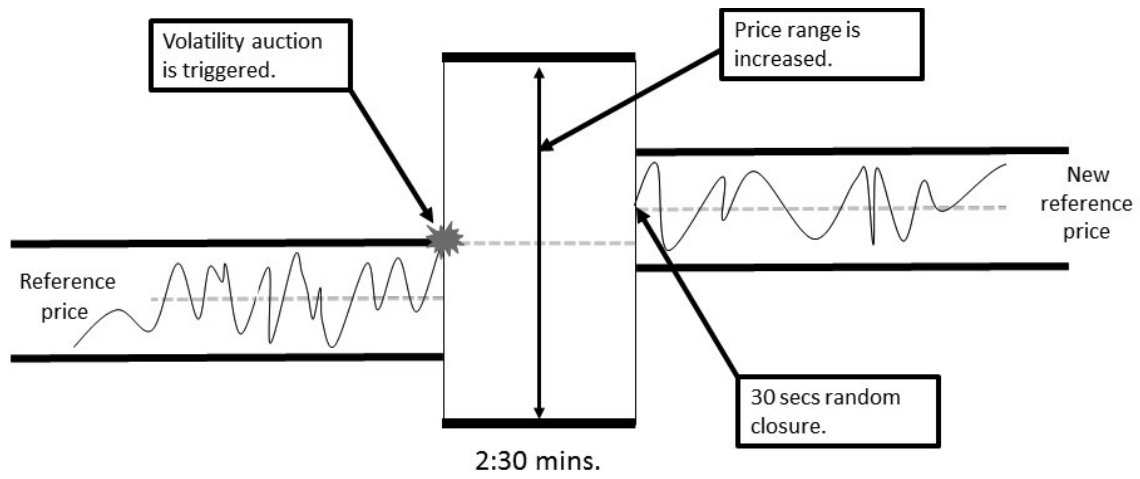
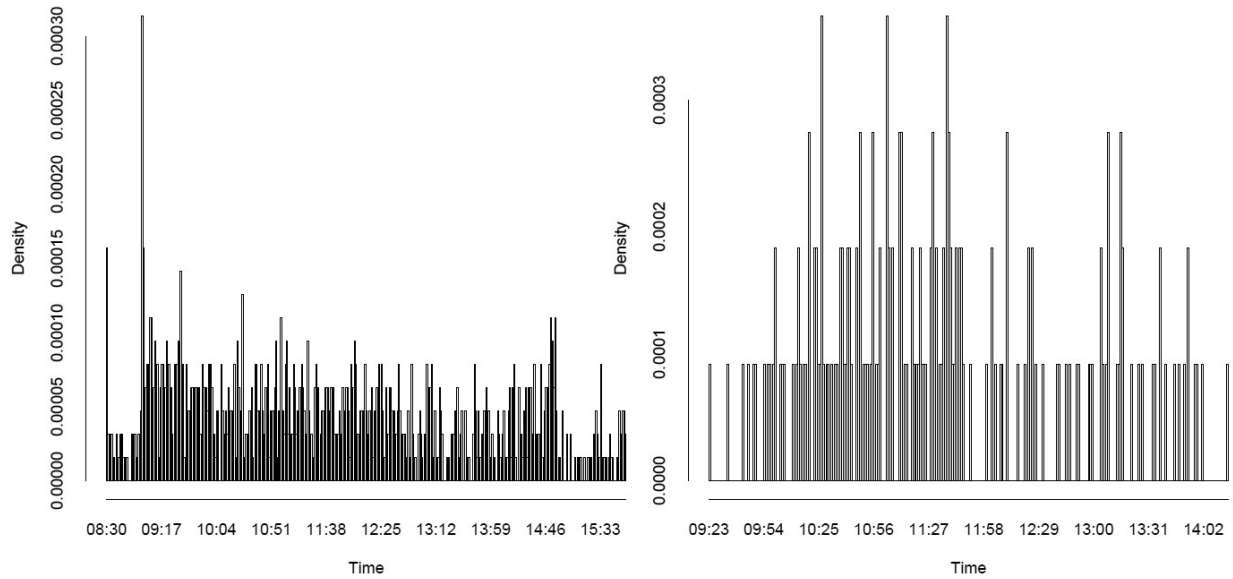


Figure 1 Volatility auction mechanism.

Source: BVC.



(a) Histogram of all 1062 auctions identified from August 2010 to August 2012.

(b) Histogram of 184 auctions identified as viable for the implementation of the synthetic portfolio method from August 2010 to August 2012.

Figure 2 Volatility auctions identified from August 2010 to August 2012.

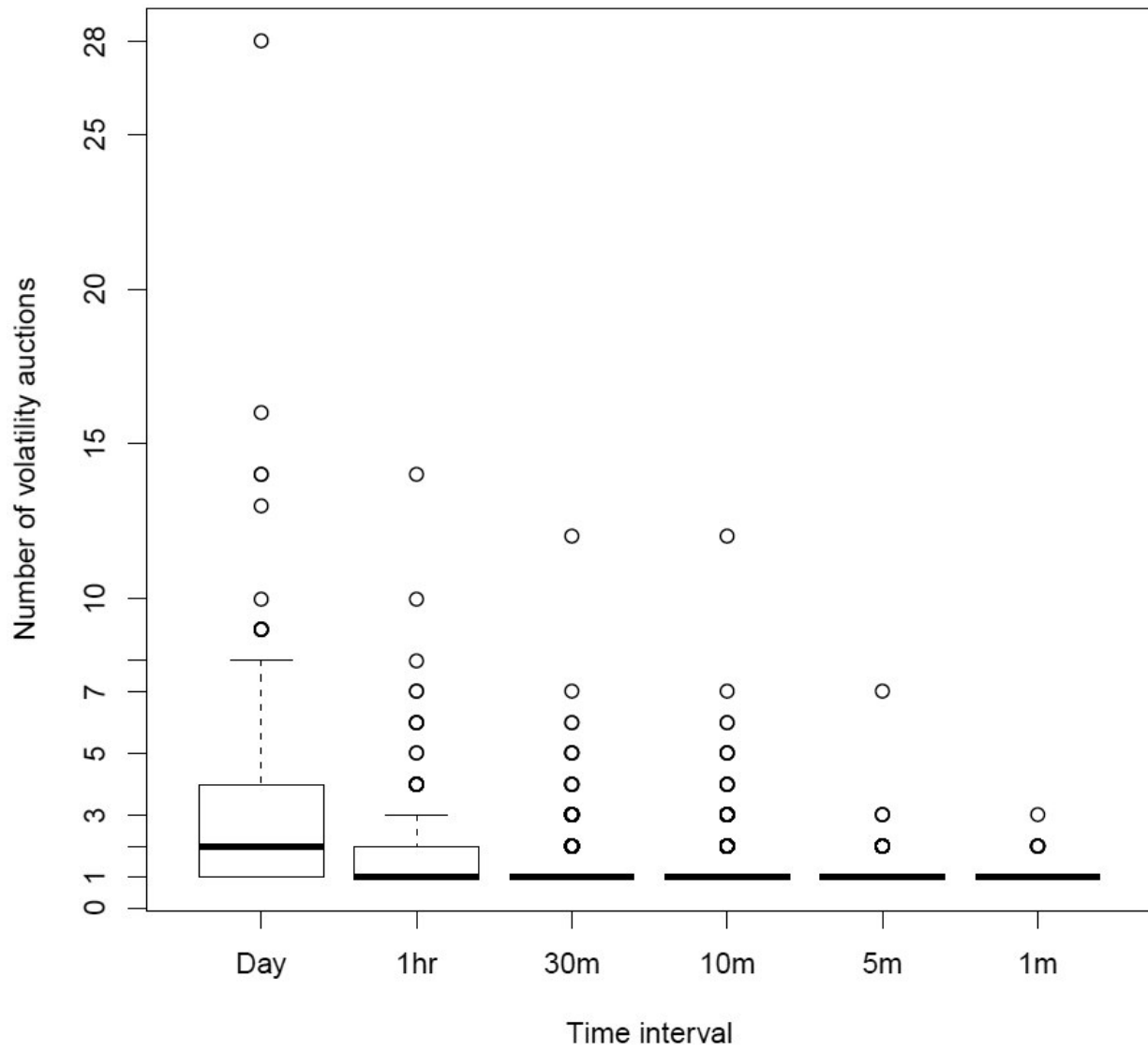


Figure 3 Number of volatility auctions within a predefined time interval.

Notes: The time intervals are: during the trading day (Day), within 1 hour (1hr), or within 30,10,5 or 1 minute(s).

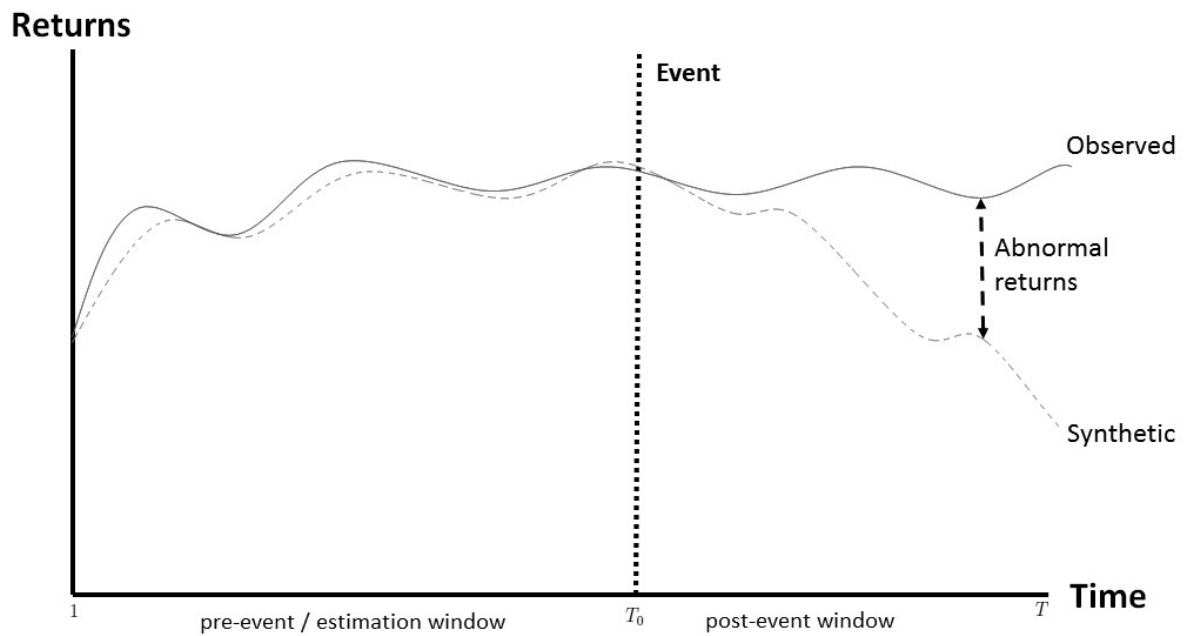
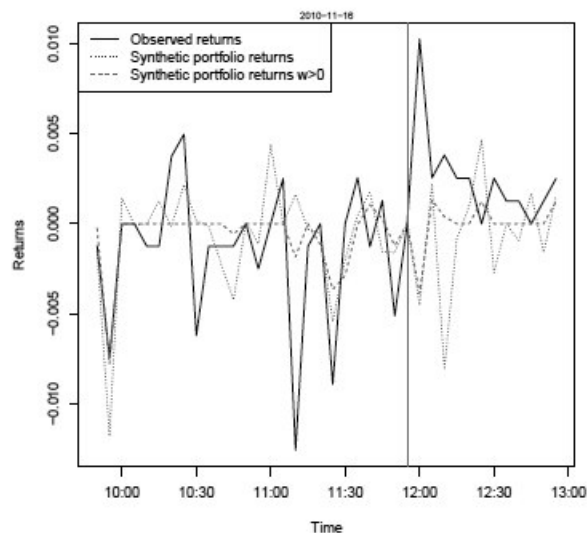
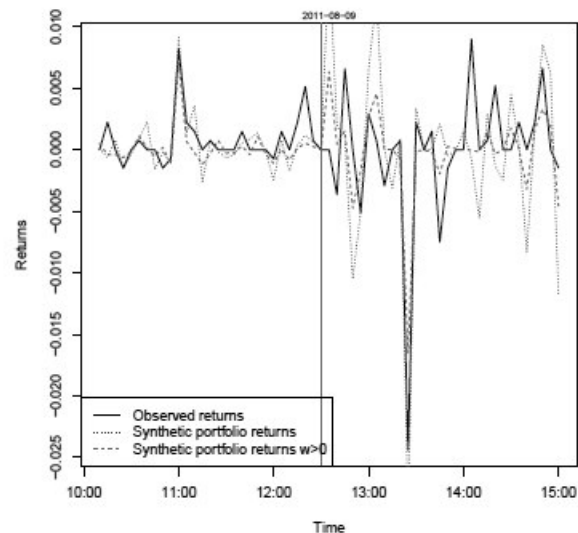


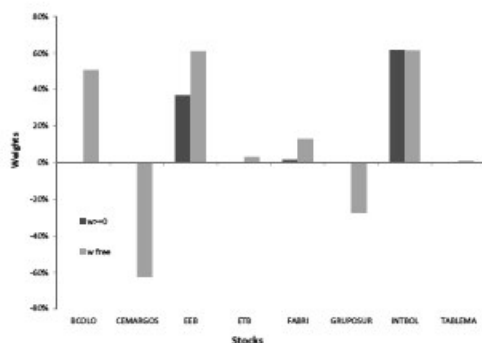
Figure 4 Synthetic portfolio method for event studies in market microstructures.



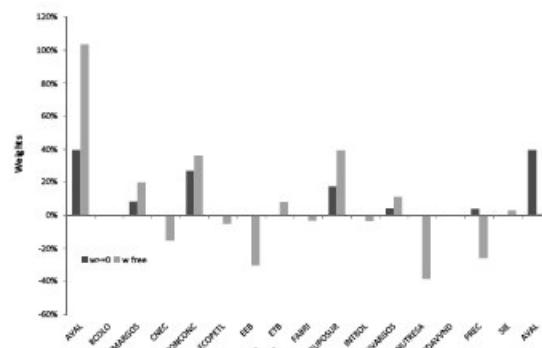
(a) Observed and synthetic returns for ECOPETL



(b) Observed and synthetic returns for PFBCOLO



(c) Synthetic portfolio weights tracking ECOPETL



(d) Synthetic portfolio weights tracking PFBCOLO

Figure 5 Synthetic portfolio.

Notes: Panels (a) and (b) illustrate the five-minute observed returns (solid line), synthetic returns with portfolio weights above or equal to zero (dashed line) and synthetic returns with unrestricted portfolio weights (dotted line) of ECOPETL and PFBCOLO over the trading day. We observed a call auction (the event) taking place at the time indicated by the red vertical line. The vertical line also determines the pre-event/estimation window and the post-event/forecasting window. Panels (c) and (d) indicate the estimated weights of the synthetic portfolio for ECOPETL and PFBCOLO. These weights are estimated using the observed returns in the pre-event window, for both the restricted and the un-restricted portfolio optimization.

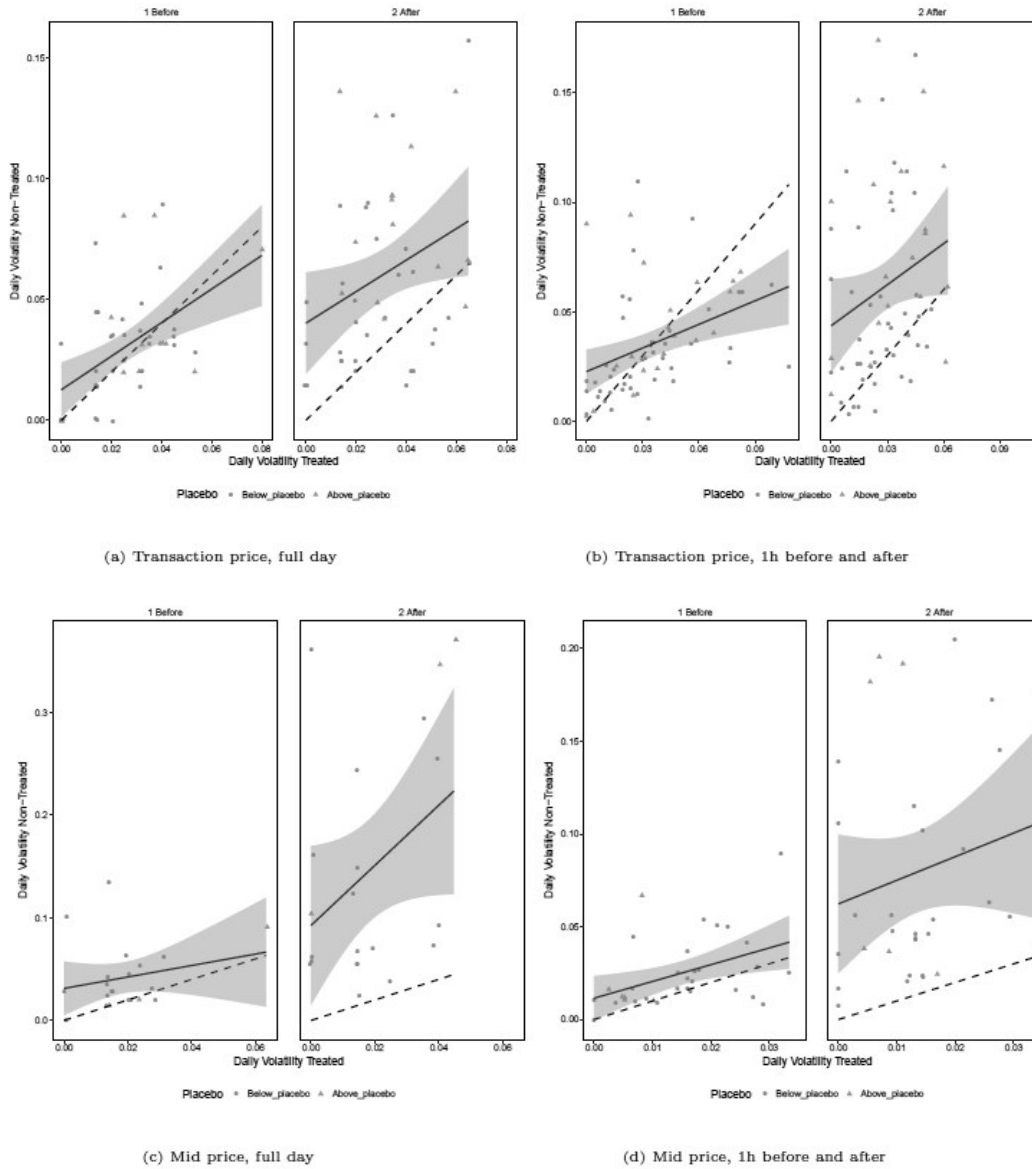


Figure 6. Impact of volatility auctions on volatility.

Notes: Each panel illustrates two scatter plots of the estimated five-minute (daily) realized volatilities before (on the left) and after the volatility auctions (on the right). The elements in the scatter plot indicate the volatility of the asset that is affected by the auction (treated, x-axis) and the non-treated synthetic portfolio (y-axis). Blue triangles (red circles) indicate auctions where the post-event estimation of the volatility using the synthetic portfolio attain a value above (below) the 95th percentile of the distribution over the placebo test. In each plot the dashed black line indicates the curve under which the volatility of the treated and the non-treated is exactly the same. The solid blue line is the OLS fitted line using the data points and the gray area is the 95th confidence interval around this line. If the estimated solid blue line is close to the dashed line before the auction then we assume that the matching is correct in the estimation window (before the auction). The solid blue lines estimated with the data points before and after the action give an idea of the effect of the volatility auctions on the non-treated (potential outcome), that is, a larger intercept after the auction (on the right) indicates the average volatility that would have been expected had the auction not taken place. In panels (a) and (b), the realized volatilities are estimated using five-minute returns based on mid-prices (quote data), whereas panels (c) and (d) provide estimated volatilities from trades. In panels (a) and (c), the realized volatilities before and after the auction are measured using the continuous trading information for the full day. In panels (b) and (d), the realized volatilities before and after the auction are measured using the continuous trading information for only one hour before and after the auction.

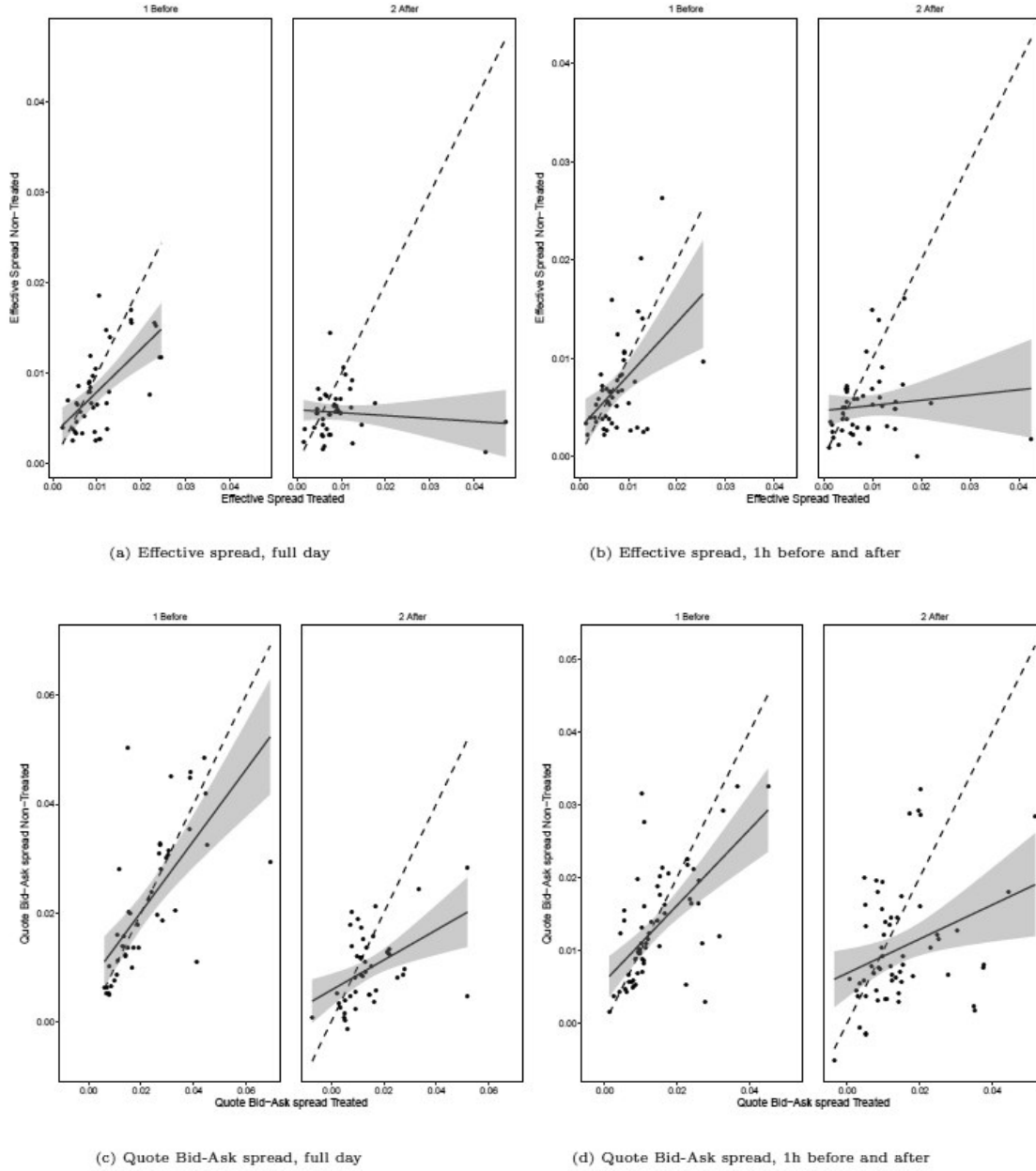


Figure 7 Impact of volatility auctions on liquidity.

Notes: Each panel illustrates two scatter plots of the average spread before (on the left) and after the volatility auctions (on the right). The elements in the scatter plot indicate the spread of the asset that is affected by the auction (treated) and the spread of the non-treated synthetic portfolio. In each plot the dashed black line indicates the curve under which the spread of the treated and the non-treated is exactly the same. The solid blue line is estimated using the data points and the gray area is the 95th confidence interval around this line. If the estimated solid blue line is close to the dashed line before the auction, then we assume that the matching is correct in the estimation window (before the auction). The estimated solid blue lines before and after the action provide a measure the effect of the volatility auctions on the non-treated (potential outcome), that is, a larger intercept after the auction indicates a wider average spread that would have been expected had the auction not taken place. In panels (a) and (b), the spreads are measured using the effective spread based on transaction prices and quotes. In panels (c) and (d), the spreads are measured using bid and ask prices (quote data). In panels (a) and (c), the average spreads before and after the auction are measured using the continuous trading information for the full day. In panels (b) and (d), the average spreads before and after the auction are measured using the continuous trading information for only one hour before and after the auction.

| Information for all day of trading | | Before auction | | | After auction | | | Difference | | | % of Auctions | | |
|------------------------------------|-----------|----------------|----------|--------|---------------|----------|--------|------------|-----------|-----------|---------------|----------|--------|
| | | Treated | Controls | Market | Treated | Controls | Market | Treated | Controls | Market | Treated | Controls | Market |
| Average return | Trades | 0.03% | 0.00% | 0.01% | 0.00% | 0.00% | 0.00% | -0.03%** | 0.00 | 0.00 | 0.13 | 0.11 | 0.14 |
| Average return | Mid-Price | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00%** | 0.00%* | 0.00 | 0.21 | 0.09 | 0.11 |
| Volatility (daily) | Trades | 2.35% | 0.41% | 0.46% | 2.60% | 0.37% | 0.46% | 0.25%** | 0.00 | 0.00 | 0.61 | 0.43 | 0.34 |
| Volatility (daily) | Mid-Price | 2.77% | 0.62% | 0.57% | 1.90% | 0.86% | 0.49% | -0.88%*** | 0.00 | -0.08%*** | 0.76 | 0.71 | 0.48 |
| Quote Bid-Ask Spread | | 1.80% | 3.22% | | 1.44% | 2.50% | | 0.00 | -0.72%*** | | 0.72 | 0.93 | |
| Effective Spread | | 0.81% | 0.74% | | 0.72% | 0.57% | | 0.00 | -0.17%*** | | 0.61 | 0.81 | |
| Bid Depth | | 38.12 | 93.65 | | 32.85 | 102.97 | | -5.27 | 9.33*** | | 0.77 | 0.74 | |
| Ask Depth | | 44.53 | 102.42 | | 51.83 | 115.51 | | 7.30 | 13.09*** | | 0.84 | 0.71 | |
| Spread Depth | | 0.04% | 0.06% | | 0.02% | 0.05% | | -0.01%*** | -0.02%*** | | 0.74 | 0.80 | |
| Turnover | | 32.11 | 29.01 | | 24.47 | 27.97 | | -7.64 | -1.04 | | 0.59 | 0.66 | |

| 1 hour before and after auction | | Before auction | | | After auction | | | Difference | | | % of Auctions | | |
|---------------------------------|-----------|----------------|----------|--------|---------------|----------|--------|------------|-----------|----------|---------------|----------|--------|
| | | Treated | Controls | Market | Treated | Controls | Market | Treated | Controls | Market | Treated | Controls | Market |
| Average return | Trades | 0.02% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | -0.02%*** | -0.01% | 0.00% | 0.10 | 0.13 | 0.09 |
| Average return | Mid-Price | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.33 | 0.09 | 0.08 |
| Volatility (daily) | Trades | 2.54% | 0.42% | 0.50% | 2.57% | 0.41% | 0.51% | 0.03% | -0.01% | 0.01% | 0.55 | 0.29 | 0.23 |
| Volatility (daily) | Mid-Price | 1.69% | 0.30% | 0.51% | 1.28% | 0.28% | 0.48% | -0.41%** | -0.02% | -0.03%** | 0.71 | 0.45 | 0.19 |
| Quote Bid-Ask Spread | | 1.17% | 2.97% | | 1.18% | 2.80% | | 0.02% | -0.17%*** | | 0.61 | 0.73 | |
| Effective Spread | | 0.64% | 0.80% | | 0.68% | 0.65% | | 0.03% | -0.15%*** | | 0.46 | 0.81 | |
| Bid Depth | | 38.78 | 92.38 | | 37.25 | 98.28 | | -1.53 | 5.90** | | 0.62 | 0.37 | |
| Ask Depth | | 49.54 | 101.98 | | 49.37 | 108.41 | | -0.16 | 6.43* | | 0.58 | 0.43 | |
| Spread Depth | | 0.03% | 0.06% | | 0.02% | 0.05% | | 0.00% | -0.01%*** | | 0.57 | 0.63 | |
| Turnover | | 30.45 | 29.47 | | 24.38 | 29.70 | | -6.07 | 0.23 | | 0.40 | 0.59 | |

Table 1 Descriptive Statistics of the variables of interest before and after the volatility auction.

Notes: The tables contain the medians on the variables of interest using the information for the sample of feasible auctions using the trade and quote data sampled over 5 minute intervals. The table on the top used all the available information during the trading day before and after the auction, to compute the descriptive statistics. The table in the bottom only considers the available information up until one hour before and after the volatility auction. The first two panels contain the median measures of the variables of interest across all of the auctions before and after. Each of these set of columns has the information for the asset that is affected by the auction (treated), the average value for the controls (the assets that are trading at the same time but are not affected by the volatility auction) and the relevant market index (COLCAP). We use the cross section of actions to measure the difference between before and after the volatility auction (excluding a 5 minute interval before and after). We use t-test and ratio test, to ascertain the statistical significance of the differences (*, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively). In addition, for each individual auction we test the null hypothesis that each of the variables of interest is statistically equivalent before and after the auction. In the last columns, we report the percentage of auctions where we can reject the null hypothesis indicating that the variables are statistically equivalent before and after the volatility auctions.

| Estimation Window Performance | | | | | | | | |
|---|--|----------------------------|--|--|--|----------------------------|--|-----|
| RMSE of Returns | | | | % of Auctions where we reject $H_0: \sigma_{\tilde{w}_t}^2 = \sigma_{\tilde{w}_t^s}^2$ | | | | |
| Potential Outcome Model Synthetic | | | | Potential Outcome Model Synthetic | | | | |
| AR1 | CAPM | $\sum w_{\tilde{w}_t} = 1$ | $\sum w_{\tilde{w}_t} = 1; w_{\tilde{w}_t} \geq 0$ | AR1 | CAPM | $\sum w_{\tilde{w}_t} = 1$ | $\sum w_{\tilde{w}_t} = 1; w_{\tilde{w}_t} \geq 0$ | |
| Trades | 0.0036 | 0.0036 | 0.0065 | 0.0039 | 61% | 61% | 55% | 45% |
| Mid-Price | 0.0042 | 0.0039 | 0.0242 | 0.0044 | 67% | 62% | 59% | 52% |
| Post Event Window Performance | | | | | | | | |
| % of Auctions where volatility is above the 95th percentile of the Placebo distribution | | | | | | | | |
| Until market close | | | | 1 hour after the event | | | | |
| Potential Outcome Model Synthetic | | | | Potential Outcome Model Synthetic | | | | |
| $\sum w_{\tilde{w}_t} = 1$ | $\sum w_{\tilde{w}_t} = 1; w_{\tilde{w}_t} \geq 0$ | | | $\sum w_{\tilde{w}_t} = 1$ | $\sum w_{\tilde{w}_t} = 1; w_{\tilde{w}_t} \geq 0$ | | | |
| Trades | 36% | | | 39% | 12% | | | |
| Mid-Price | 42% | | | 39% | 11% | | | |

Table 2 Performance of event method methodologies and synthetic matching.

Note: The table on the top compares a series of measures of performance over the estimation window (in-sample fit) of synthetic matching with respect to traditional event study methodologies. The first measure on the left is the root mean square error between the observed returns and the normal (using a univariate AR1 process or the market model-CAPM-) or synthetic portfolio with unrestricted or non-negative weights. The second measure on the right is based on a two-sample ratio test on the difference of scale parameters (Ansari-Bradley test) for each individual auction comparing the volatility of the treated and the synthetic portfolio in the estimation window. The table indicates the percentage of auctions where the null hypothesis is rejected. The table in the bottom is based on the placebo test in Abadie et al. (2010) based on synthetic matching in the post event window. The test is applied to the randomization of units between the treatment and control group in each auction. The tables indicate the percentage of auction where the estimated variance for the true treatment variable is above the 95th percentile of the placebo distribution.

| | | After auction we take all available data to the end of the trading day | | Available data one hour before and after the auction | |
|--------------|----------------------------|--|-------------|--|-------------|
| | Difference (After- Before) | Treated | Non-Treated | Treated | Non-Treated |
| Volatility | Trades -observed | 1.02%* | 2.20%*** | -0.21% | 1.98%*** |
| | Mid Price -fundamental | 0.00% | 7.90%*** | -0.28% | 3.8%*** |
| Liquidity | Quote Bid-Ask Spread | -0.70%*** | -1.00%*** | 0.09% | -0.30%*** |
| | Effective Spread | -0.20% | -0.30%*** | 0.04% | -0.17%*** |
| | Bid Depth | -11.37*** | 23.38*** | -7.43*** | 17.56*** |
| | Ask Depth | 0.70 | -2.08 | 2.58 | 9.82 |
| | Spread Depth | -0.01%* | -0.02%*** | 0.00%** | 0.00%** |
| Trading Act. | Turnover | 3.60 | 0.66 | -4.44 | -6.74 |

Table 3 Impact on market quality of the volatility auction.

Note: The table illustrates the difference between the median value across the cross section of auctions of the variables of interest before and after the auction. In the first column, we provide estimates based on the data available before and after the auction, while in the second column only with the data one hour before and after the auction. The two-sample Wilcoxon test is performed to determine the statistical significance of the difference. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.