Call Auction Volatility Extensions

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Current draft: Oct. 31, 2017

Volatility extensions in closing auctions are designed to improve the efficiency of the closing price. We hypothesize that the channel for the efficiency increase is that extensions improve market integrity and investor trust in the auction mechanism. We confirm that the introduction of a volatility extension indeed reduces extraordinary closing price volatility, deters market manipulation strategies, and makes the auction more attractive to investors. Our findings provide guidance to policy makers who are due to introduce volatility extensions at NYSE and NASDAQ in 2017. In the European Union, call auction volatility curbs become mandatory under Markets in Financial Instruments Directive II in 2018.

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1 Introduction

At the opening of US equity markets on August 24, 2015, prices dropped sharply following overnight turmoil in global markets. The opening call auction was restricted by a type of volatility curb, a *price collar*, which became binding and led to volatility spillovers into the continuous trading session. In the minutes after opening, large order imbalances triggered trading halts in numerous stocks and exchange-traded funds. According to the *Financial Times,* more than a thousand securities were affected and hundreds of them experienced repeated trading halts before prices stabilized.[1] The episode illustrates how price collars constrain the key function of the opening (and reopening) mechanism: price discovery. In response to this problem, US exchanges—including NASDAQ, the New York Stock Exchange (NYSE), and NYSE Arca—have suggested replacing auction price collars with another type of volatility curb: a *volatility extension* (U.S. Securities and Exchange Commission, or SEC, 2016).

When a call auction operates with a volatility extension, large price swings trigger an extension of the order entry phase (batching period). The extension signals to investors that volatility is unusually high and allows them to reconsider their orders. Similar to circuit breakers in continuous trading, the mechanism is designed to mitigate transitory volatility. Whereas circuit breakers are ubiquitous in equity markets and have been thoroughly analyzed in the literature (see reviews by Harris, 1998; Kim and Yang, 2004), the effects of volatility extensions remain unknown.

The aim of this paper is to analyze the effects of introducing a call auction volatility extension (CAVE). Our aim is motivated by several factors. First, the current regulatory development puts call auction volatility curbs in focus. In addition to the plan of US markets to introduce the mechanism, all European Union (EU) trading venues will be required to apply volatility curbs in their call auctions by January 2018.[2] Second, call auctions are

[1] "ETF providers question US trading limit rules," *Financial Times*, August 28, 2015, https://www.ft.com/content/27d3ec3a-4d86-11e5-b558-8a972297718. For a detailed account of the events on August 24, 2015, see also BlackRock (2015).

[2] Article 19, §1, of the Markets in Financial Instruments Directive (MiFID) II reads, "Trading venues shall ensure that appropriate mechanisms to automatically halt or constrain trading are operational at all times during

increasingly important in terms of market share. Driven by the increase in passive investing and small trade sizes in continuous trading, closing call volumes in US markets have increased from 3.6% of the average daily volume in 2011 to 5.5% in 2017.[3] In the EU, closing call auctions account for more than 10% of the average daily volume (ITG, 2014). Third, because the closing price is used as the reference price for the performance evaluations of mutual funds and brokers, as well as the settlement price for derivatives, it is important for it to be accurate and resilient to attempts at manipulation (Hillion and Suominen, 2004). Volatility curbs are potentially important to mitigate the risk of auction price manipulation.

We use a unique quasi-natural experiment to analyze the effect of a volatility extension. On December 1, 2014, the NASDAQ Nordic equity market introduced volatility extensions in their call auctions. The new policy applied to all opening call auctions operated by NASDAQ Nordic, which includes the Stockholm, Copenhagen, and Helsinki listings. For the closing call auctions, however, only the Stockholm segment was affected. The excluded Copenhagen and Helsinki segments, which operate under close to identical market structure conditions as the Stockholm market, provide us with an ideal control group.[4]

To assess the effect of volatility extensions, we use models on circuit breakers in the continuous trading session as a starting point. Circuit breakers typically lead to a reduction in transitory volatility, but at the cost of delayed price discovery in times of high fundamental volatility, volatility spillovers (Lehmann, 1989), and aggressive trading (see the "magnet effect" described by Subrahmanyam, 1994). CAVEs are similar to circuit breakers in that transitory volatility is potentially mitigated, but we see no reason for volatility spillovers or the magnet effect to apply. Based on this, our first hypothesis states that volatility extensions are beneficial to the accuracy of the closing call auction price.

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trading hours" (European Securities and Markets Authority, 2015, p. 268). MiFID II is due to enter into force for all EU members in January 2018.

[3] See https://www.greenwich.com/press-release/stock-trading-volumes-gravitate-open-and-closing-auctions.

[4] According to personal communication with NASDAQ Nordic, that the Copenhagen and Helsinki segments are excluded from the volatility extension mechanism in the closing call auction is an outcome of negotiations with local market participants. This fact strengthens the experimental setup, since the treatment choice is arguably unrelated to the market quality variables of interest.

To understand the channels underlying an improvement in closing price efficiency, we analyze the effect that volatility extensions have on market integrity and the attractiveness of the call auction. We define a market with high integrity as one that has low market abuse activity.[5]

We predict that volatility extensions improve market integrity by deterring market manipulation. Hillion and Suominen (2004) argue that the use of the closing price in performance and portfolio evaluation, as well as in derivative contract settlement, makes it susceptible to manipulation. A volatility extension signals to market participants that the call auction is extraordinarily volatile. The warning signal undermines the profitability of manipulative behavior, such as last-second cancellations. We expect a higher degree of market integrity to improve investor confidence and increase auction attractiveness. In addition, regardless of the source of volatility, the extension grants auction participants a chance to reconsider their orders. Domowitz and Madhavan (2001) argue that investors value the ability to modify orders in times of large price changes.

We find strong support for the hypothesis on closing price efficiency. After the introduction of volatility extensions, the incidence of extraordinary closing price volatility at the market, measured in accordance to the volatility bands of the CAVE, is reduced by about 40% for small-cap stocks. For mid-cap stocks, there are no such instances after the introduction of CAVEs. For large caps, there is virtually no extraordinary closing price volatility, neither before nor after the event. This suggests either that the closing mechanism functions well without the extension or that the volatility bands are too wide. Accordingly, we focus our subsequent analysis on small- and mid-cap stocks.

By zooming in on batching period activity, we are able to analyze market integrity and auction attractiveness. To capture manipulative behavior in the closing call auction, we measure the volume of order cancellations occurring in the last seconds of the auction. This measure falls by 14% in the treatment group relative to the control group. We also document a decrease of about 3% in the average order book imbalance in the last 10 seconds of the

[5] For an extensive discussion of the definition of market integrity, see Austin (2017).

auction. The evidence indicates that the volatility extension improves market integrity at the end of the trading day. Furthermore, we document that the auction attracts trading volume from the continuous trading session, that a greater portion of the auction trading volume is due to orders submitted at the beginning of the batching period, and that the auction indicative price is less volatile and is established earlier in the batching period. Our interpretation is that investors put more trust in the auction mechanism, which could be due to the reduction of manipulative strategies.

Our investigation contributes to several strands of the literature. First, there is a vast literature on how closing call auctions can help to improve the efficiency of the closing price (Schwartz, 2001) and overcome order imbalances and information asymmetries at the end of the trading day (Madhavan, 1992; Economides and Schwartz, 1995; Pagano and Schwartz, 2003; Aitken, Comerton-Forde, and Frino, 2005; Barclay, Hendershott, and Jones, 2008; Kandel, Rindi, and Bosetti, 2012). Efficient closing prices are important for several reasons. The closing price functions as the reference price for derivatives and index calculations and is commonly used to benchmark the performance of portfolio managers and brokers. We contribute to the closing call auction literature by analyzing how volatility extensions influence the quality of the auction mechanism. Furthermore, we introduce new measures of batching period quality, emphasizing the importance of market integrity and investors' trust in the auction mechanism.

We also contribute to the emerging literature that emphasizes the importance of call auction design (McCormick, 2001; Comerton-Forde and Rydge, 2006; Kandel, Rindi, and Bosetti, 2012, who stress the importance of the choice of the algorithm used to match the batch orders). Cordi, Foley, and Putniņš (2015) conduct a comprehensive study of the effects that the closing call auction and its design have on market efficiency and integrity. Our study contributes to the literature by focusing specifically on volatility extensions.

Finally, our study relates to the more general literature on volatility curbs and extends it to the call auction setting. Previous studies in this field focus on the continuous trading session and find that price limits do not tend to reduce volatility in the stock market (Kim and Yang, 2004). Our results indicate that CAVEs reduce indicative price volatility and have a deterrent effect on market manipulation, which lowers the incidence of extraordinary closing price volatility. The effect of volatility curbs on trading behavior is sparsely analyzed in the literature. Previous studies in this vein focus mainly on the magnet effect of circuit breakers, as described by Subrahmanyam (1994). We contribute to the literature by analyzing whether volatility extensions increase market integrity and investors' trust in the call auction mechanism.

Our evidence indicates that volatility extensions are beneficial in terms of closing price efficiency, market integrity, and auction attractiveness. Given the regulatory agendas in the United States and the EU, we expect increasing interest in volatility extensions going forward.

2 Call auction volatility curbs around the world

Table 1 presents an overview of call auction volatility curbs implemented at equity exchanges around the world.[6] Panel A provides information on the call auction mechanisms at European exchanges and Panel B lists non-European stock exchanges that currently have volatility curbs implemented.

[INSERT TABLE 1 HERE]

There are two types of volatility curbs: i) a *volatility extension*, which extends the batching period if the uncross would otherwise violate the volatility bands, and ii) a *price collar*, which restricts prices to fall within the volatility bands. The volatility extension is the most common volatility curb at EU exchanges and the subject of our empirical investigation. The only EU exchange (to our knowledge) applying price collars is Euronext. By January 3, 2018, all exchanges governed by MiFID II must implement volatility curbs (see footnote 1).[7]

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[6] The authors are thankful to Sean Foley for providing information on the closing mechanisms and call auction designs of numerous exchanges around the world.

[7] Borsa Istanbul and SIX Swiss Exchange, where no volatility curbs are currently applied, are not governed by MiFID II.

The length of the volatility extensions varies from one minute (at the Oslo Børs) to 10 minutes (at the Toronto Stock Exchange). When triggered at Xetra, the closing call auction is extended until the exchange manually decides to terminate it. Another design variation is the number of possible extensions. NASDAQ Nordic specifies that the auction can be extended only once, whereas the London Stock Exchange and Tel Aviv Stock Exchange operate a second extension if the uncross price after the first extension still falls outside the volatility bands. Finally, volatility extensions can be used in combination with other price stabilization mechanisms. For instance, at the Spanish Stock Exchange, the auction extension is followed by a 30-second randomization of the uncross.

In the US equity markets, the NYSE, NYSE Arca, and NASDAQ all operate price collars for the opening call auction, as well as for the reopening auction following trading halts. NYSE Arca applies price collars for the closing auction too, whereas NASDAQ uses a volatility extension. The NASDAQ volatility extension is done in one-minute increments, until there is no market order imbalance and there is no large price movement during the last 15 seconds of the batching period. At the NYSE, under unusual market conditions or large order imbalances, the designated market maker may delay the auction execution. This type of volatility extension applies to the opening, reopening, and closing auctions alike. The rules for the NYSE extensions are principle based, meaning that there are no exact specifications for, for example, the volatility bands and the extension duration.

Following the problems with the reopening auctions on August 24, 2015 (described above), US exchanges aim to harmonize the reopening procedures across trading venues and to institute volatility extensions. According to the exchanges' joint filing with the SEC (2016), reopening auctions following trading halts should be extended if the uncross price violates preset volatility bands or if there is a market order imbalance. The auction should then be extended by five-minute increments, with gradually increasing volatility bands until the uncross can take place.

3 Theoretical predictions

We review the theoretical literature on volatility curbs with the aim of formulating hypotheses on the effects of CAVEs. To our knowledge, there is no theoretical work on volatility curbs specific to the call auction setting, so we use the literature on circuit breakers as our starting point.

To assess the merit of volatility curbs, it is important to distinguish between fundamental and transitory volatility (Fama, 1989; Greenwald and Stein, 1991; Harris, 1998). Whereas fundamental volatility contributes to price discovery, transitory volatility may be due to the order imbalances of uninformed traders, transaction costs, or attempted price manipulation. The benefit of volatility curbs is that they potentially mitigate transitory volatility but they may also delay price discovery (for a more detailed discussion, see the review by Kim and Yang, 2004).

The discussion of transitory and fundamental volatility extends easily to the call auction setting. Just like a circuit breaker in continuous trading, a volatility extension may mitigate transitory volatility in the call auction by offering a period of relief during which traders can reconsider their orders. By definition, in case of fundamental volatility, the delay in price discovery also carries over to the call auction setting.

Two aspects of circuit breakers that arguably do not apply to volatility extensions are volatility spillovers and the magnet effect. Lehmann (1989) argues that, if price limits are narrowly set, they may cause a spillover of information to the subsequent trading opportunity. This is consistent with the opening of US markets on August 24, 2015, where price collars were in operation. In the case of volatility extensions, the spillover does not apply. The auction uncross is not constrained to fixed price limits; it is merely delayed. In the context of closing auctions, whereas the volatility extension delays price discovery by a few minutes, a price collar can delay price discovery until the next morning.

A well-known drawback of circuit breakers is the magnet effect. Subrahmanyam (1994) shows that, when the traded price is close to the volatility bands, traders become more aggressive for fear of not being able to trade if the limit is hit, thereby amplifying the volatility. In a call auction setting with a volatility extension, a magnet effect is unlikely. Because all trades are concentrated at the uncross, aggressive trading does not lead to earlier execution. In contrast, the volatility extension may deter aggressive trading, since such orders could lead to delayed execution.[8]

Based on the discussion above, we formulate our first hypothesis.

H1: The introduction of a volatility extension improves the efficiency of the closing price by reducing the transitory volatility.

To understand the channels of an improvement in the closing price efficiency, we now consider how a volatility extension may influence the incentives of market participants. We formulate hypotheses related to market integrity and auction attractiveness.

Market integrity is a key priority in the design of the closing price mechanism. The closing price is used as a benchmark for performance evaluation and portfolio valuation, as well as the settlement price for derivative contracts. Hillion and Suominen (2004) point out that, if appropriate safeguards are not in place, the closing price may be subject to manipulative strategies. Though the authors argue that the use of a call auction generally mitigates the scope for price manipulation, Madhavan and Panchapagesan (2000) show that prices may still be distorted if the auction order flow is thin and the order imbalance is high. Comerton-Forde and Rydge (2006) present empirical evidence showing that the call auction design (degree of transparency and matching algorithm design) can improve the efficiency of the auction price.

A trigger of the CAVE sends a clear signal to market participants that there is an extraordinary amount of volatility in the auction. We predict that this warning signal to other market participants deters manipulative strategies and thus improves market integrity.

[8] In the context of price collars in the call auction, the magnet effect may apply. A strategic trader who expects high fundamental volatility can submit orders early in the batching period at the prevailing price limit. The gain of this strategy would be a high time priority at a price that is expected to be better than the unconstrained equilibrium price.

H2: The introduction of a volatility extension improves call auction market integrity.

Economides and Schwartz (1995) argue that call auctions are good for market efficiency because they consolidate the order flow in time and space (across trading venues). Accordingly, policy makers should design call auctions to incentivize traders to participate in them. Investors are arguably more likely to participate if they trust that the auction mechanism maintains high market integrity.

In addition, Domowitz and Madhavan (2001) argue that call auction participants value the possibility of canceling and modifying orders during the batching period. The volatility extension sends a clear signal to market participants when volatility reaches extraordinary levels and it allows them to reconsider their orders. We expect this signal to reduce the call auction order monitoring cost, making the mechanism more attractive to market participants.

Based on this reasoning, we formulate our final hypothesis.

H3: The introduction of a volatility extension improves the attractiveness of the call auction mechanism.

4 Empirical setting

In this section, we present the institutional details of NASDAQ Nordic with a focus on call auctions and volatility extensions. We then present the data and sample employed for the study. Finally, we present the market characteristics for each market segment.

4.1 Volatility extensions at NASDAQ Nordic

NASDAQ Nordic is the eighth largest stock exchange in Europe (based on turnover statistics for November 2014; see Federation of European Securities Exchanges, 2014) and the primary venue for most Danish, Finnish, Icelandic, and Swedish equities. The trading system INET is also used for the NASDAQ exchange in the US.

NASDAQ Nordic operates a continuous limit order book market from 9:00 AM to 5:25 PM, except for Copenhagen listings, which closes at 4:55 PM.[9] The market is open from Monday to Friday, except for public holidays. On trading days before public holidays, the closing time is 12:55 PM.[10]

4.1.1 Call auctions at NASDAQ Nordic

The closing auction batching period starts immediately after the end of continuous trading. During the batching period, limit and market orders may be entered, modified, and canceled at any time. Hidden orders are allowed but must have a volume of at least EUR 50,000.[11] At the time of the uncross, trading takes place if there are orders to buy and sell at crossed or equal prices. The uncross price is set at the level that maximizes the uncross volume. Orders execute in accordance to price–internal–visibility–time priority.[12] On November 15, 2015, NASDAQ Nordic introduced randomized uncross times for the closing call auction, such that the uncross can vary randomly within a 30-second period. In our sample, however, the uncross time is fixed.

During the batching period, the trading system disseminates the state of the order book (price and aggregate volume visibly posted at the best bid and ask prices), indicative uncross information (auction price and volume), as well as imbalance information (volume and direction, buy or sell, of orders that will not be executed in the auction). The indicative uncross information and the imbalance information are updated in real time as the state of the order book evolves.

[9] Stockholm and Copenhagen follow Central European time (UTC+1) and Helsinki follows Eastern European time (UTC+2). For all references to time, we use UTC+1.

[10] The technical details presented here are based on the INET market model, which holds complete information about the market structure. The document is available at http://www.nasdaqomx.com/digitalAssets/90/90375_nasdaq-omx-nordic-market-model-2.23.pdf.

[11] We cannot observe hidden orders in our data, but Hagströmer and Nordén (2013) report that hidden and partially hidden orders are rare in the Swedish stock market, constituting only 0.7% of all limit orders in a sample of large-cap stocks in August 2011 and February 2012. In comparison to the 44% that Bessembinder, Panayides, and Venkataraman (2009) report for a sample of 100 stocks on Euronext Paris in 2003, the use of hidden orders at NASDAQ Nordic is very low.

[12] Internal priority means that orders with price priority that are posted by the same exchange member on different sides of the trade (e.g., on behalf of different clients) are executed against each other, regardless of their visibility and time priority. The same priority rules apply for continuous trading.

4.1.2 Volatility extension

NASDAQ Nordic introduced CAVEs on December 1, 2014.[13] The policy change affects the opening call auctions of the Stockholm, Copenhagen, and Helsinki listings (operated from 8:00 AM to 9:00 AM), as well as the closing call auction of the Stockholm listings.[14] The volatility extension does not apply to other call auctions operated by NASDAQ Nordic, including scheduled mid-day call auctions (at 1:30 PM for small and mid caps) and unscheduled call auctions following trading halts.

The volatility extension is triggered if the auction price calculated at the original time of the uncross deviates significantly from a reference price. The reference price for the closing call is the price of the last trade during the continuous trading session. The batching period for the closing call auction is normally five minutes, followed by the uncross (implying that the uncross is at 5:30 PM for the Stockholm and Helsinki segments and at 5:00 PM for the Copenhagen segment). The volatility extension prolongs the batching period by three minutes. At the end of the extension, the uncross takes place, regardless of what the auction price is.

The volatility bands determining when the auction extension is triggered are typically set at ±10% of the reference price for the opening call and at ±5% for the closing call. The volatility bands are tighter for stocks that are part of the large-cap indexes (OMXS30 for Stockholm, OMXH25 for Helsinki, and OMXC20 for Copenhagen) and wider for penny shares and certain illiquid stocks. See the Appendix for the exact volatility band definitions.

[13] NASDAQ Nordic refers to the volatility extensions as *auction safeguards.* The technical details and scope regarding the auction extensions are based on official NASDAQ documents available at https://globenewswire.com/news-release/2014/08/28/661951/0/en/IT-INET-Introduction-of-trading-safeguards-to-opening-and-closing-auctions-in-NASDAQ-OMX-Nordic-and-Baltic-exchanges-80-14.html. NASDAQ also published a Q&A about the introduction (see http://www.nasdaqomx.com/digitalAssets/95/95742_q-a-auction-safeguards-and-extension-nov-2014.pdf.

[14] NASDAQ Nordic also includes the Reykjavik listings, where both the opening and closing call auctions are subject to auction extensions. We exclude the Reykjavik segment because the volatility bands of the CAVE are determined differently from the other segments. Outside NASDAQ Nordic, the volatility extensions were introduced at the same time as for NASDAQ Baltic (including the Riga, Tallinn, and Vilnius listings) and First North (a NASDAQ-operated venue for growth companies in Europe), for both the opening and closing auctions.

4.2 Data and sample

We access tick-by-tick data on trades, quotes, and auction uncross information from Thomson Reuters Tick History (TRTH), supplied by the Securities Industry Research Centre of Asia-Pacific. All the data are time stamped to the microsecond. The trade data include prices, volumes, and qualifiers indicating, among other things, whether a trade is executed in the auction or in the continuous limit order book. The quote data include order book information such as the aggregate order volumes available at each price level. Specific to the auction mechanism, TRTH reports the indicative uncross information and the imbalance information during the batching period, as well as uncross information at the end of the auction. The prices and volumes disseminated in the indicative uncross information are denoted *Indicative Price* and *Indicative Volume*, respectively. The corresponding variables for the actual auction uncross are denoted *Uncross Price* and *Uncross Volume*. The order imbalance is denoted *Order Imbalance*.

Our sample includes large-, mid-, and small-cap stocks listed at NASDAQ Nordic. We retain stocks that remain in the same size segment (small cap/mid cap/large cap) throughout the entire sample period and that have trading activity for all the months of the sample. In total, 546 out of 586 stocks are included in the sample (285 listed in Stockholm, 125 in Helsinki, and 136 in Copenhagen). We include data from six months before and six months after the event, implying a sample period from June 1, 2014, to May 31, 2015.

4.3 Market characteristics

Table 2 reports the characteristics of the markets that we study based on the six months preceding the introduction of the CAVE. As expected, the trading volume of stocks at NASDAQ Nordic increases with market capitalization. Large caps also have a substantially higher volume in the closing call auction (≃15% for the treatment group and 12% for the control group) than do mid caps (≃6% and 7% for the treatment and control groups, respectively) and small caps (2% for both the treatment and control groups). The closing call auction volumes signal that investors are more attracted by the call auction mechanism for large-cap stocks than for mid and small caps.

[INSERT TABLE 2 HERE]

An important observation that can be made from Table 2 is that our treatment group (NASDAQ Stockholm) is, in many respects, similar to the control group (NASDAQ Helsinki and NASDAQ Copenhagen). There are 285 stocks in the treatment group, compared to 261 in the control group. The average market capitalization is around EUR 1.9 billion in the treatment group and around EUR 1.5 billion in the control group. The tendency of a higher closing call auction volume in larger stocks is reflected in both the treatment and the control group.

5 Methodology

The fact that NASDAQ Nordic introduces a CAVE in one of its geographical segments while keeping the other segments unaffected provides a quasi-natural experiment setup. Our identification of the effects of the volatility extension on auction quality and attractiveness hinges on the fact that observed changes in the treatment group can be benchmarked to changes observed in the control group. The validity of this approach is leveraged by the fact that the treatment and control groups operate under almost identical market structures and have similar characteristics in terms of market capitalization and trading activity (as discussed in Section 4.3).

5.1 Difference-in-differences analysis

We employ a difference-in-differences regression model to assess the impact of the CAVE while controlling for factors unrelated to the event. The regression analysis also controls for permanent differences between the treatment and control groups.

Specifically, to investigate the influence of the event on a variable $Y_{i,t}$ (where i is an index for stocks and t is an index for trading days) we set up the following regression model:

$$Y_{i,t} = \alpha + \beta_1 Post_{i,t} + \beta_2 Treatment_{i,t} + \beta_3 Post_{i,t} Treatment_{i,t} + \boldsymbol{\gamma Controls}_{i,t} + \epsilon_{i,t}, \quad (1)$$

where $Post_{i,t}$ is a dummy variable that equals one for trading days from the event date onward and $Treatment_{i,t}$ is a dummy variable that equals one for stocks in the treatment group. The parameter of primary interest is β_3, which captures the effect of the introduction of a volatility extension in the treatment group relative to the control group and $\boldsymbol{Controls}_{i,t}$ is a matrix of control variables, including *Volatility* and *Volume,* with *Volatility* computed as the difference between the highest and lowest daily traded prices, divided by the average midpoint, and *Volume* as the natural logarithm of the daily traded euro (EUR) volume.

5.2 Measures of closing price efficiency

To evaluate our first hypothesis (H1), which states that the volatility extension improves the efficiency of the closing price, we consider two measures of closing price volatility.

We define the first metric, *Extraordinary Closing Price Volatility*, in accordance with the volatility bands of the CAVE. Specifically, we form a binary variable indicating for each stock–day whether the closing call auction volatility bands are violated. The volatility thresholds are based on price changes from the last trade of the continuous trading session to the auction uncross. For the treatment group post-event period, this count equals the incidence of volatility extensions. For other stock–days, we use the volatility bands described in the Appendix to detect hypothetical triggers. We define hypothetical triggers as price changes that would have caused an extension had the CAVE been in operation.[15]

Our second measure of closing price volatility is designed to capture volatility from the end of the continuous trading session to the end of the closing call auction. We define *Closing Price Volatility* as

$$Closing\ Price\ Volatility = |\ln(Uncross\ Price) - \ln(Reference\ Price)|, \qquad (2)$$

[15] Our data do not contain explicit information on the threshold applied to each stock. We infer the thresholds from the prices of the stocks and additional information on the liquidity group, stock category, and segment found in documents published by NASDAQ Nordic (2014a, 2014b, 2015). We validate our hypothetical trigger algorithm by applying it to the treatment group in the post-event period, for which we have information on actual volatility extensions (provided to us by NASDAQ Stockholm). We obtain an almost perfect match, which indicates that our algorithm successfully replicates that used by NASDAQ Nordic.

where $Reference\ Price$ is the price of the last trade in the continuous trading session. All variables are observed on a stock-day frequency. For brevity the indexes i and t are henceforth omitted.

5.3 Measures of market integrity

In accordance with our second hypotheses, we design three novel measures to capture the degree of market integrity. We design the three metrics to reflect manipulative behavior, implying that they are all decreasing in market integrity.

One way to manipulate call auctions is to signal a trading interest during the batching period only to withdraw it shortly before the uncross. Accordingly, the prevalence of batching period cancellations may reflect the degree of manipulative behavior. We define *Cancellation Rate* as the ratio of the batching period cancellation activity and uncross trading activity:

$$Cancellation\ Rate = \frac{Cancellations_{CCA}}{Uncross\ Volume}, \tag{3}$$

where $Cancellations_{CCA}$ is the EUR value of orders that are cancelled during the batching period of the closing call auction, $Uncross\ Volume$ is expressed in EUR.

Market participants attempting to game the auction are likely to cancel large orders shortly before the scheduled uncross. Our second measure of market integrity, *Late Cancellation Rate,* zooms in on the last 10 seconds of the auction and is defined as

$$Late\ Cancellation\ Rate = \frac{Cancellations_{CCA}^{Late}}{Uncross\ Volume}, \tag{4}$$

where $Cancellations_{CCA}^{Late}$ is the same as $Cancellations_{CCA}$, except that it is restricted to the last 10 seconds of the batching period.

Another way to evaluate market integrity is to consider the auction imbalance. The auction imbalance is the signed volume of orders that are not executed in the auction uncross. The exchange disseminates the expected imbalance in real time to market participants during the batching period.[16] Market participants attempting to abuse the auction may submit large unrepresentative orders late in the batching period to move the uncross price away from the fundamental value. Our third measure of market integrity, *Late Order Imbalance*, is designed to capture such behavior and is defined as

$$Late\ Order\ Imbalance = \frac{Order\ Imbalance_{CCA}^{Late}}{Order\ Imbalance_{CCA}^{Early}}\ , \tag{5}$$

where $Order\ Imbalance_{CCA}^{Late}$ is the average *Order Imbalance* of the last ten seconds of the batching period; and $Order\ Imbalance_{CCA}^{Early}$ is the average *Order Imbalance* of the rest of the batching period (that is, the first four minutes and fifty seconds). Both imbalance metrics are expressed in EUR.

5.4 Measures of auction attractiveness

To evaluate our third hypothesis, we consider five different measures of auction attractiveness.

The most straightforward way to assess whether the auction becomes more attractive is, perhaps, to investigate whether traders migrate to or from the auction mechanism. We define the *Relative Auction Volume* as

$$Relative\ Auction\ Volume = \frac{Uncross\ Volume}{Total\ Volume}, \tag{6}$$

where $Total\ Volume$ is the total trading volume in the stock-day, including the closing call. We expect the $Relative\ Auction\ Volume$ to be increasing in auction attractiveness.

Another aspect of call auction attractiveness may be retrieved by zooming in on investor activity during the batching period. For example, if investors are not concerned by closing price volatility, they are arguably more likely to submit orders early in the batching period to gain time priority. If investors worry that the closing price is inefficient or that the market lacks integrity, they may postpone their orders until the end of the batching period,

[16] The expectation is based on the assumption that there are no more submissions, cancellations, or modifications before the auction uncross.

when more information is revealed. We design four novel measures based on batching period activity.

The exchange disseminates the first indicative uncross information when there are crossing prices in the call auction order book. We denote the time of the first indicative uncross information $t_{first\ indicative}$, and the scheduled uncross time (in the absence of a volatility extension) $t_{uncross}$. We then define

$$First\ Indicative\ Time\ to\ Uncross = t_{uncross} - t_{first\ indicative}, \quad (7)$$

where time is measured in seconds. We postulate that a higher *First Indicative Time to Uncross* signals higher auction attractiveness, because it demonstrates that investors trust the auction mechanism enough to commit their trading interests early on.

Increasing trust in the auction mechanism can also be demonstrated in that market participants post larger orders early in the batching period. To capture this dimension of trust, we let $t_{indicative\ volume}$ denote the first time when the *Indicative Volume* equals or exceeds the *Uncross Volume*. Similar to the former measure, we define

$$Indicative\ Volume\ Time\ to\ Uncross = t_{uncross} - t_{indicative\ volume}, \quad (8)$$

where time is measured in seconds. By the same reasoning as above, we expect the $Indicative\ Volume\ Time\ to\ Uncross$ to be increasing with auction attractiveness.

An alternative way to evaluate trust in the auction mechanism is to measure the proportion of the *Uncross Volume* that is generated by orders posted early in the batching period. To this end, we define

$$Early\ Trading\ Interest = \frac{First\ Indicative\ Volume}{Uncross\ Volume} \times \frac{First\ Indicative\ Time\ to\ Uncross}{300}, \quad (9)$$

where the first term is the ratio of the *First Indicative Volume* (the *Indicative Volume* posted at $t_{first\ indicative}$) and the *Uncross Volume* (both measured in EUR); and the second term is a weighting factor that gives greater weight to orders submitted earlier in the batching period (note that the scheduled batching period duration is 300 seconds). *Early Trading Interest* is designed to be increasing with auction attractiveness.

Finally, we postulate that higher trust in the closing call auction should lead to lower volatility in the indicative price. As above, we base this reasoning on the fact that traders who trust the integrity of the market post their orders earlier in the batching period and with larger sizes. Such behavior should make the order book more resilient to liquidity shocks. We define *Indicative Price Volatility* as the difference between the highest and lowest indicative prices disseminated during the batching period ($Indicative\ Price_{high}$ and $Indicative\ Price_{low}$):

$$Indicative\ Price\ Volatility = \ln(Indicative\ Price_{high}) - \ln(Indicative\ Price_{low})\ . \qquad (10)$$

We expect the $Indicative\ Price\ Volatility$ to be decreasing with auction attractiveness.

6 Does the volatility extension affect call auction quality?

In this section, we present the results of our event study and relate them to our empirical hypotheses.

6.1 Closing price efficiency

In Figure 1, we present a bar chart showing the number of stock–days featuring *Extraordinary Closing Price Volatility*. The bars are grouped by stock segments (as classified by NASDAQ OMX), treatment and control markets, and the periods before and after the event. We find that, after the CAVE introduction, *Extraordinary Closing Price Volatility* drops in all size segments for the treatment stocks. Note that this result is not mechanical, because we base the volatility measure on the scheduled closing time and not the actual closing time if there is a volatility extension. We find no corresponding reduction for the control group, supporting the view that the decline in volatility is due to the introduction of the CAVE.

[INSERT FIGURE 1 HERE]

The reduction in *Closing Price Extraordinary Volatility* is consistent with H1 and indicates that the CAVE influences trader behavior in the auction. In contrast to the magnet effect described by Subrahmanyam (1994), CAVEs appear to deter orders that would otherwise trigger the volatility extension.

Another important finding is that the decline of *Extraordinary Closing Price Volatility* is concentrated in small- and mid-cap stocks. The introduction of CAVEs is associated with a reduction in the number of triggers of about 40% for small-cap stocks and 100% for mid-cap stocks. In the large-cap segment, there is only one hypothetical trigger in the period before the introduction and none afterward. The low incidence of *Extraordinary Closing Price Volatility* in the large-cap segment may be due to a well-functioning closing mechanism for large caps, which would be consistent with the high closing call volumes reported in Table 2. Alternatively, the volatility bands may be set too wide. Large stocks typically have lower volatility and higher liquidity than mid and small caps, yet their default volatility bands are the same (except for the OMXS30 index, which is the leading stock index in the market). Given that volatility bands rarely affect large-cap stocks, we focus our subsequent analysis on small- and mid-cap stocks. The results for the large-cap stocks are generally weaker and are available in the Online Appendix.

Next, we investigate whether the reduction in volatility carries over to our measure of average volatility, *Closing Price Volatility*. Table 3 shows the difference-in-differences coefficient estimates. The coefficient of primary interest is β_3, which corresponds to $Post_{i,t}Treatment_{i,t}$ and captures the effect of the introduction of CAVEs in the treatment group relative to the control group. To produce unbiased standard errors, we cluster the standard errors by stock and trading day (Petersen 2009; Thompson 2011). We find a negative (-0.0003) but statistically insignificant influence of the introduction of CAVEs on average volatility.

[INSERT TABLE 3 HERE]

Overall, we conclude that extraordinary volatility in the closing price is reduced by the introduction of a volatility extension in the call auction, but there is no evidence of a general reduction in volatility. Notably, the outcome is consistent with the purpose of the auction extensions, that is, to reduce the prevalence of extreme price swings without interfering with price discovery. In the next two sections, we study the potential channels for the reduction in extraordinary volatility events: market integrity and auction attractiveness.

6.2 Market integrity

Market integrity is a key priority for regulators, but it is not straightforward to measure. While we cannot observe manipulative strategies directly, we can infer their prevalence by analyzing market integrity. For instance, if market participants cancel fewer orders after the introduction of CAVEs, particularly in the final seconds shortly before market closure, it indicates a decrease in traders' manipulative behavior. Similarly, a reduction of order imbalances points toward a decrease in closing price manipulation.

Figure 2 reports the average evolution of the auction cancellation rate (Panel A) and the auction imbalances (Panel B) for small and mid-cap stocks belonging to our treatment group. Specifically, the auction cancellation rate is defined as in Eq. (3), but for 20-second intervals instead of the whole batching period. We define the order imbalance as the average *Order Imbalance* (measured in SEK) for each 20-second interval of the batching period. While visually the effects of CAVEs on the first four minutes of the auction are unclear, there is a perceivable reduction in both the cancellation rate and the auction imbalance towards the end of the auction, supporting the hypothesis of improved market integrity.

[INSERT FIGURE 2 HERE]

To see whether the conclusions from our visual inspection of Figure 2 hold up statistically, we benchmark the market integrity variables to the control group. Table 4 presents the results of the difference-in-differences regression analysis on market integrity. We find strong evidence of improved market integrity, consistent with H2. The variable *Cancellation Rate*, which captures the cancellation intensity in the closing auction, decreases significantly for the treatment group relative to the control group. The treatment group *Cancellation Rate* before the event is 1.061 (1.050 + 0.011 = 1.061), showing that the amount of cancellations during the batching period, on average, is slightly higher than the trading volume in the uncross. Following the introduction of volatility extensions, it falls to 1.045 (1.061 + 0.021 – 0.037 = 1.045), which is a drop of 1.5%. At the same time, the control group experiences a significant increase.

[INSERT TABLE 4 HERE]

Consistent with Figure 2, the fall in volume cancellations for the treatment group is more substantial during the last 10 seconds of the batching period. The variable *Late Cancellation Rate* decreases significantly by 13.5% (from 1.12 to 0.969) for the treatment group, while the control group remains unchanged. The drop in cancellations, especially in the last seconds of the auction, indicates that CAVEs improve market integrity.

The variable *Late Order Imbalance* captures whether the average order imbalance is larger in the last 10 seconds than in the rest of the batching period. For the treatment group before the event, this variable is close to one (0.928 + 0.045 = 0.973), indicating that the order imbalance is, on average, lower late in the auction than otherwise. After the introduction of the CAVE, *Late Order Imbalance* decreases relative to the control group, albeit the effect is only statistically significant at the 10% confidence level. The decrease in auction order book imbalance indicates an improvement of market integrity and suggests that the introduction of CAVEs discourages traders from submitting or canceling unrepresentative large orders just prior to market closure with the intention of manipulating closing prices.

6.3 Auction attractiveness

We now turn to the investigation of H3, where CAVEs make the closing call auction more attractive to investors, partially because the increased integrity improves trust in the auction mechanism. Figure 3 depicts the evolution of two measures of auction attractiveness for small- and mid-cap stocks at NASDAQ Stockholm. The most straightforward way to evaluate auction attractiveness is perhaps in the trading volume. Panel A of Figure 3 reports the average evolution of the *Indicative Volume* available during the batching period before and after the introduction of volatility extensions. The parallel upward shift of the volume curve shows that the *Indicative Volume* is higher throughout the batching period after the volatility extension is introduced. In line with our hypothesis, the evidence suggests that the volatility extension succeeds in attracting liquidity to the auction.

[INSERT FIGURE 3 HERE]

Auction attractiveness can also be assessed by looking at the timing of order submissions. If market participants trust the auction mechanism, they are more likely to submit their orders early in the batching period. Panel B of Figure 3 depicts the cumulative frequency of the time of the first indicative price, $t_{first\ indicative}$. The upward shift of the curve shows that, after the implementation of CAVEs, the indicative price is established earlier in the batching period. This piece of evidence suggests that traders are less concerned about closing price volatility.

Table 5 presents the results of the difference-in-differences regression analysis for the five measures relating to auction attractiveness. We find strong evidence of improved auction attractiveness, consistent with H3. In relative terms, *Relative Auction Volume* for the treatment group increases following the event. According to the coefficient estimates, the closing auction volume for the treatment group falls from 5.56% to 4.56%, but the fall is even stronger for the control group (from 8.55% to 6.49%). This result, consistent with Figure 3, Panel A, indicates that the volatility extension successfully attracts trading volume to the auction.

[INSERT TABLE 5 HERE]

Zooming in on the batching period activity again, the metric *First Indicative Time to Uncross* captures whether investors submit orders earlier in the batching period. We find that *First Indicative Time to Uncross* increases by 3.08 seconds (from 223.86 to 226.94 seconds) for the treatment group, which is a statistically significant improvement relative to the control group. This finding shows that the indicative price is established 3.08 seconds earlier after the event. Though the economic significance of this result is difficult to identify, it is in line with the hypothesis that the volatility extension increases traders' trust in the auction mechanism.

The conjecture of increased auction attractiveness is reinforced by the positive and significant results for *Indicative Volume Time to Uncross,* which captures whether traders submit orders earlier and of greater volume. Our results show that, after the introduction of CAVEs, *Indicative Volume Time to Uncross* improves by 8.78 seconds for the treatment group relative to the control group. Similarly, *Early Trading Interest* improves after the introduction of volatility extensions*.* This metric reflects whether a greater fraction of the final traded volume is concentrated at the beginning of the batching period. The variable *Early Trading Interest* increases significantly by 1.7% (from 0.699 to 0.711) for the treatment group, while the control group experiences a significant decrease of 2% (from 0.685 to 0.671).

Finally, *Indicative Price Volatility* brings further support for the hypothesis of increased auction attractiveness. We record a statistically significant reduction (-0.002) of *Indicative Price Volatility* for the treatment group relative to the control group after the introduction of CAVEs.

Overall, our results show strong support for H3. They are consistent with Domowitz and Madhavan's (2001) point that market participants value the possibility of modifying or canceling orders in the batching period, particularly in times of high volatility. The finding that investors post orders earlier in the batching period, that the early orders are of greater volume, and that the indicative price becomes less volatile indicates that investors become less wary of auction manipulation. Taken together, the evidence indicates that the market participants' trust in the auction mechanism improves due to the introduction of volatility extensions.

7 Conclusion

This paper analyzes the effects of introducing a volatility extension in the closing call auction. We use a quasi-natural experiment setup based on the introduction of a volatility extension at NASDAQ Stockholm to examine the effects of CAVEs. Similar policies are due to be implemented at major US exchanges in 2017 and will become mandatory for all EU exchanges in 2018. Given the regulatory agendas, we expect increasing interest in volatility extensions. Understanding the effects of CAVEs is hence increasingly relevant to regulators and policy makers.

Our results show that CAVEs reduce extraordinary closing price volatility as defined by the volatility bands but do not have a significant effect on average closing price realized volatility. To understand the channels underlying the improvement of closing price efficiency, we evaluate the effects that CAVEs have on market integrity and auction attractiveness by zooming in on the quoting activity in the batching period. We find that market integrity improves. Market participants cancel fewer orders after the introduction of CAVEs, particularly in the final seconds of the auction, and the order imbalance shortly before market closure is reduced. Furthermore, we find that market participants' trust in the auction mechanism improves with CAVEs. Investors post orders earlier in the batching period, the early orders are of greater volume, and the indicative price volatility is lower. We interpret the evidence as indicating investors are less wary of auction manipulation when a volatility extension is in operation.

We find sharp differences between small-, mid-, and large-cap stocks. For large-cap stocks, there are virtually no cases of extraordinary volatility events, neither before nor after the introduction of the volatility extension. We conclude that either the closing mechanism for large stocks functions well without CAVEs or the volatility bands are set too wide. Future research could investigate how to optimally set volatility bands, potentially in relation to stock characteristics. Furthermore, our analysis of the effects of volatility extensions could be extended to price collars, which are the second most important type of volatility curbs found in call auctions.

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Table 1. Call Auction Volatility Curbs around the World

The table presents information about call auction volatility curbs at European exchanges (Panel A) and at exchanges in the rest of the world (Panel B). The column *Volatility Curb* indicates whether such a mechanism is in place; *Type of Volatility Curb* shows whether it is a *Price Collar* or a *Volatility Extension,* as well as details about the extension frequency and duration; *and Call Auction Session* specifies which auction mechanisms are subject to the volatility curb. Under a price collar, the auction execution price is constrained within preset price bands. A volatility extension is triggered when, at the time of the auction uncross, the hypothetical execution price lies outside the predefined price bands (with the exception of the NYSE, see footnote b in Panel B).

Panel A: European Exchanges

Exchange	*Volatility Curb*	*Type of Volatility Curb*	*Call Auction Session*
Borsa Istanbul	No	-	-
Euronext (Lisbon, Amsterdam, Brussels, Paris, London)	Yes	Price collar	Open, close
London Stock Exchange	Yes	Volatility extension (up to twice, 2 min)[a]	Open, intraday, close
NASDAQ Baltics	Yes	Volatility extension (once, 3 min)	Open, close
NASDAQ Copenhagen and Helsinki	Yes	Volatility extension (once, 3 min)	Open
NASDAQ Stockholm and Iceland	Yes	Volatility extension (once, 3 min)	Open, reopen, close
Oslo Børs	Yes	Volatility extension (once, 1 min)	Open, reopen, close
Spanish Stock Exchange	Yes	Volatility extension (once, 2 min + 30 sec randomization)	Open, close
SIX Swiss Exchange	No	-	-
Xetra	Yes	Volatility extension (once, flexible duration)	Open, close

[a] If the hypothetical execution price after the first auction extension still lies outside the predefined price bands, a second extension is triggered.

Panel B: Non-European Exchanges

Exchange	*Type of Volatility Curb*	*Call Auction Session*
North America		
NASDAQ	Price collar	Open, close
	Volatility extension (1-min increments)[a]	Reopen
NYSE	Price collar	Open, reopen
	Volatility extension[b]	Open, reopen, close
NYSE Arca	Price collar	Open, reopen, close
Toronto Stock Exchange	Volatility extension (once, 10 min)	Close
Asia		
Hong Kong Stock Exchange	Price collar	Close
Moscow Exchange	Volatility extension (once, 3 min)	Close
Tel Aviv Stock Exchange	Volatility extension (up to twice, 3–4 min)[c]	Open, close
Africa		
Johannesburg Stock Exchange	Volatility extension (once, 5 min)	Open, intraday, close

[a] There is no limit on the number of extensions. The closing auction is extended successively if, after each one-minute extension, there is a market order imbalance *or* if the indicative uncross price moves by more than 5% or USD 0.50 (whichever is greater) in the last 15 seconds of the batching period.
[b] There are no preset rules on the range of deviation or the length of the auction extension. The extension is triggered at the discretion of the designated market maker under unusual market conditions and when order imbalances may cause large price dislocations.
[c] If the hypothetical execution price after the first auction extension still lies outside the predefined price bands, a second extension is triggered.

Table 2. Market Characteristics

This table reports summary statistics of the sample markets (NASDAQ Stockholm, Helsinki, and Copenhagen) for large, mid, and small caps. The statistics are averaged across trading days from June 1 to November 30, 2014. Data on *Trading Currency*, *Number of Stocks,* and *Market Capitalization* are obtained as of November 30, 2014, from NASDAQ Nordic (2014b). The variable *Daily average trading volume* is calculated for different trading sessions as the sum of intraday trading volumes, measured in EUR. Trading volumes in Swedish kronor (SEK) and Danish kroner (DKK) are converted into EUR using the following exchange rates: SEK/EUR = 9.266 and DKK/EUR = 7.441 (official exchange rates on November 28, 2014, according to the European Central Bank). The variable *Daily Average Turnover* is computed as the ratio between *Daily Average Trading Volume* and average *Market Capitalization*.

	Treatment Group			***Control Group***					
	NASDAQ Stockholm			NASDAQ Helsinki			NASDAQ Copenhagen		
	Large	Mid	Small	Large	Mid	Small	Large	Mid	Small
Trading Currency	SEK	SEK	SEK	EUR	EUR	EUR	DKK	DKK	DKK
Number of Stocks	87	91	107	32	37	56	27	25	84
Market Capitalization (million EUR)									
Average	5 923.8	440.9	61.4	8 680.9	622.7	48.9	4 318.0	449.6	47.1
Min	47.7	16.7	0.8	250.2	55.9	0.4	103.2	63.5	0.4
Max	50 349.5	1 671.1	315.7	77 479.7	1 536.3	310.6	25 054.3	1 536.7	171.1
Total	515 371.6	43 213.0	6 879.8	243 065.1	16 814.1	4 841.7	151 128.4	17 535.2	2 875.7
Daily Average Trading Volume (million EUR)	1209.03	73.91	10.33	405.75	23.82	1.95	481.51	28.91	3.51
Opening call auction (%)	1.51	2.33	4.48	1.92	3.05	6.22	1.57	2.34	4.72
Continuous trading (%)	83.61	92.15	93.10	86.54	88.37	90.17	86.77	90.78	92.43
Intraday call auction (%)	-	-	0.60	-	0.97	0.76	-	0.86	0.70
Closing call auction (%)	14.89	5.51	1.82	11.54	7.60	2.85	11.66	6.02	2.15
Daily Average Turnover	0.23	0.17	0.15	0.17	0.14	0.04	0.32	0.16	0.12

Table 3. Difference-in-Differences Analysis of the Average Closing Price Volatility

This table reports estimated effects of the introduction of a CAVE on the closing price volatility. The parameter estimates correspond to the following unbalanced panel difference-in-differences regression:

$$Y_{i,t} = \alpha + \beta_1 Post_{i,t} + \beta_2 Treatment_{i,t} + \beta_3 Post_{i,t} Treatment_{i,t} + \boldsymbol{\gamma Controls}_{i,t} + \epsilon_{i,t},$$

where *i* is an index for stocks and *t* is an index for trading days. The dependent variable $Y_{i,t}$ is *Closing Price Volatility*, defined as the absolute log difference between the *Uncross Price* and the price of the last trade in the continuous trading session; $Treatment_{i,t}$ is a dummy variable that takes the value one if stock *i* belongs to the treatment group (NASDAQ Stockholm) and zero otherwise; $Post_{i,t}$ is a dummy variable that takes the value one for the post-event window (December 1, 2014, to May 31, 2015) and zero for the pre-event window (June 1, 2014, to November 30, 2014); and $\boldsymbol{Controls}_{i,t}$ is a matrix of control variables including *Volatility* and *Volume,* with *Volatility* computed as the difference between the highest and lowest daily traded prices, divided by the average midpoint, and *Volume* as the natural logarithm of the daily traded EUR volume. Standard errors are corrected by double clustering on stock and day and are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	Closing Price Volatility (1)
Intercept	0.0088***
	(0.0006)
$Treatment_{i,t}$	0.0014
	(0.0008)
$Post_{i,t}$	-0.0003
	(0.0004)
$Treatment_{i,t}$ $Post_{i,t}$	-0.0003
	(0.0005)
$Volatility_{i,t}$	-0.0001
	(0.0002)
$Volume_{i,t}$	0.000*
	(0.0000)
Observations	21564
Adjusted R-Squared	0.003

Table 4. Difference-in-Differences Analysis of Market Integrity

This table reports the estimated effects of the introduction of a CAVE on market integrity. The parameter estimates correspond to the following unbalanced panel difference-in-differences regression:

$$Y_{i,t} = \alpha + \beta_1 Post_{i,t} + \beta_2 Treatment_{i,t} + \beta_3 Post_{i,t} Treatment_{i,t} + \boldsymbol{\gamma Controls}_{i,t} + \epsilon_{i,t},$$

where i is an index for stocks and t is an index for trading days. The regression is estimated for three different dependent variables that capture market integrity: *Cancellation Rate* is the ratio between the EUR volume of cancellations occurring at the closing call auction and the EUR *Uncross Volume*, *Late Cancellation Rate* is the ratio between the EUR volume cancellations occurring in the last 10 seconds of the auction and the EUR *Uncross Volume*. *Late Order Imbalance* is the ratio between the average bid–ask EUR *Order Imbalance* of the last 10 seconds of the batching period and the overall average *Order Imbalance* of the batching period (excluding the last 10 seconds). The independent variables are as follows: $Treatment_{i,t}$ is a dummy variable that takes the value one if stock *i* belongs to the treatment group (NASDAQ Stockholm) and zero otherwise; $Post_{i,t}$ is a dummy variable that takes the value one for the post-event window (December 1, 2014, to May 31, 2015) and zero for the pre-event window (June 1, 2014, to November 30, 2014); and $\boldsymbol{Controls}_{i,t}$ is a matrix of control variables including *Volatility* and *Volume*, with *Volatility* computed as the difference between the highest and lowest daily traded prices, divided by the average midpoint, and *Volume* as the natural logarithm of the daily traded EUR volume. Standard errors are corrected by double clustering on stock and day and are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	Cancellation Rate (1)	*Late Cancellation Rate (2)*	*Late Order Imbalance (3)*
Intercept	1.050***	0.921***	0.928***
	(0.007)	(0.005)	(0.005)
$Treatment_{i,t}$	0.011	0.199***	0.045***
	(0.014)	(0.029)	(0.011)
$Post_{i,t}$	0.021**	-0.001	0.008
	(0.009)	(0.006)	(0.008)
$Treatment_{i,t}$ $Post_{i,t}$	-0.037***	-0.151**	-0.032*
	(0.013)	(0.066)	(0.017)
$Volatility_{i,t}$	-0.005***	0.007	0.007***
	(0.001)	(0.005)	(0.002)
$Volume_{i,t}$	0.000	0.000*	0.000
	(0.000)	(0.000)	(0.000)
Observations	20761	4101	3564
Adjusted R-Squared	0.0004	0.01	0.001

Table 5. Difference-in-Differences Analysis of Auction Attractiveness

This table reports the estimated effects of the introduction of a CAVE on auction attractiveness. The parameter estimates correspond to the following unbalanced panel difference-in-differences regression:

$$Y_{i,t} = \alpha + \beta_1 Post_{i,t} + \beta_2 Treatment_{i,t} + \beta_3 Post_{i,t} Treatment_{i,t} + \boldsymbol{\gamma Controls}_{i,t} + \epsilon_{i,t},$$

where i is an index for stocks and t is an index for trading days. The regression is computed for five different dependent variables that capture auction attractiveness: *Relative Auction Volume* is the ratio between the *Uncross Volume* and the daily traded volume; *First Indicative Time to Uncross* is the distance, in seconds, between the time the first indicative price was disseminated in the auction and the time of the auctions' uncross, $t_{uncross}$; *Indicative Volume Time to Uncross* is the distance, in seconds, between the time when a volume at least equal to the *Uncross Volume* is recorded in the batching period and $t_{uncross}$; *Early Trading Interest* is a time-weighted ratio between the EUR volume associated with the first indicative price and the EUR *Uncross Volume*; and *Indicative Price Volatility* is the log difference between the highest and lowest *Indicative Price*. The independent variables are as follows: $Treatment_{i,t}$ is a dummy variable that takes the value one if stock i belongs to the treatment group (NASDAQ Stockholm) and zero otherwise; $Post_{i,t}$ is a dummy variable that takes the value one for the post-event window (December 1, 2014, to May 31, 2015) and zero for the pre-event window (June 1, 2014, to November 30, 2014); and $\boldsymbol{Controls}_{i,t}$ is a matrix of control variables including *Volatility* and *Volume,* with *Volatility* computed as the difference between the highest and lowest daily traded prices, divided by the average midpoint, and *Volume* as the natural logarithm of the daily traded EUR volume. Standard errors are corrected by double clustering on stock and day and are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	Relative Auction Volume (1)	*First Indicative Time to Uncross (2)*	*Indicative Volume Time to Uncross (3)*	*Early Trading Interest (4)*	*Indicative Price Volatility (5)*
Intercept	0.0855***	249.56***	161.22***	0.685***	0.009***
	(0.0062)	(3.77)	(5.84)	(0.0102)	(0.0006)
$Treatment_{i,t}$	-0.0299***	-25.70***	18.97***	0.014	0.002**
	(0.0071)	(5.13)	(6.87)	(0.0145)	(0.0009)
$Post_{i,t}$	-0.0206***	-4.21**	-9.22***	-0.014**	0.001**
	(0.0035)	(1.57)	(2.42)	(0.0066)	(0.0007)
$Treatment_{i,t}$ $Post_{i,t}$	0.0106***	7.29**	8.78**	0.026**	-0.002***
	(0.0043)	(3.42)	(3.96)	(0.0120)	(0.0008)
$Volatility_{i,t}$	0.0003	-0.43	-1.21**	-0.002	-0.001
	(0.0005)	(0.60)	(0.55)	(0.0020)	(0.0006)
$Volume_{i,t}$		0.00***	0.00***	0.000	0.000
		(0.00)	(0.00)	(0.0000)	(0.0000)
Observations	31999	34839	30964	31215	15224
Adjusted R-Squared	0.02	0.02	0.02	0.002	0.002

Figure 1. Extraordinary Closing Price Volatility

This figure shows the incidence of *Extraordinary Closing Price Volatility* before and after the introduction of volatility extensions. The bar chart reports the number of stock–days where the price change from the end of the continuous trading session to the end of the closing call auction is large enough to fulfill the conditions for an auction volatility extension. The results are reported for both the pre- and post-event periods for each market capitalization segment (small cap, mid cap, and large cap) and for the treatment group (NASDAQ Stockholm) as well as the control group (NASDAQ Copenhagen and Helsinki). The pre-event period (*Pre*) contains all trading days from June 1 to November 30, 2014. The post-event period (*Post*) contains all trading days from December 1, 2014, to May 31, 2015.

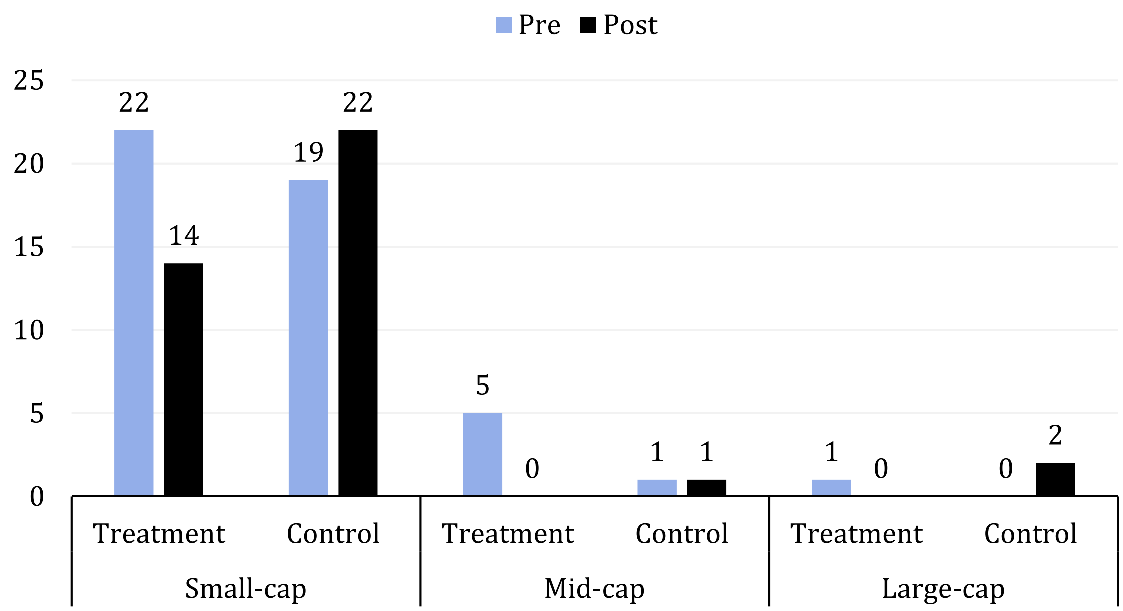
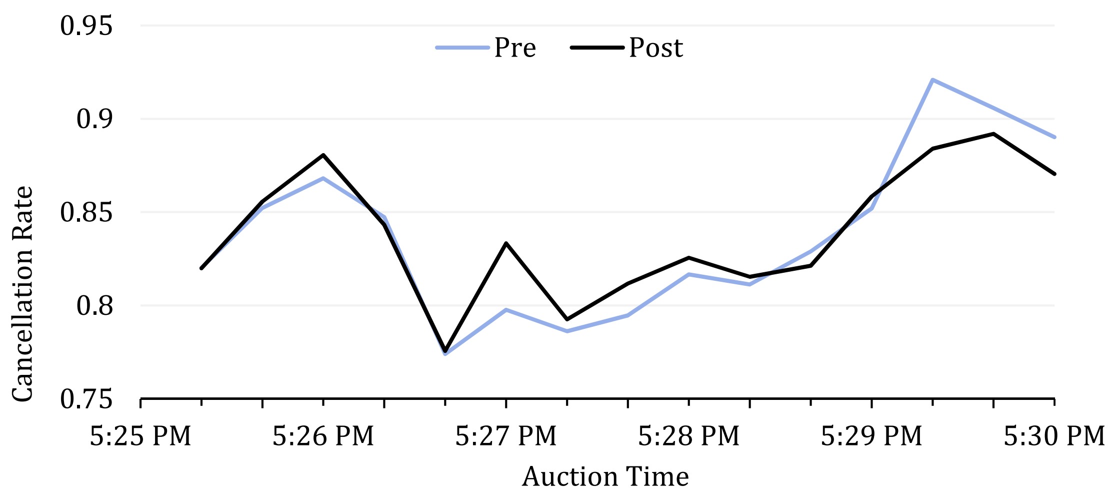


Figure 2. Measures of Market Integrity

This figure shows the cancellation rate and order imbalances during the batching period of the closing call auction at NASDAQ Stockholm. Panel A depicts the SEK value of limit orders (limit price multiplied by limit quantity) cancelled in a given period, divided by the SEK *Uncross Volume* on the same stock–day. The time series is based on a 20-second frequency for the period 5:25 PM to 5:30 PM. Panel B shows the SEK *Order Imbalance* (absolute difference between bid and ask limit quantities multiplied by their limit prices) at a one-second frequency for the period 5:25 PM to 5:30 PM. Both measures are averaged across stock–days for small- and mid-cap stocks at NASDAQ Stockholm. The pre-event period (*Pre*) contains all trading days from June 1 to November 30, 2014. The post-event period (*Post*) contains all trading days from December 1, 2014, to May 31, 2015.

Panel A: Cancellation Rate



Panel B: Order Imbalance

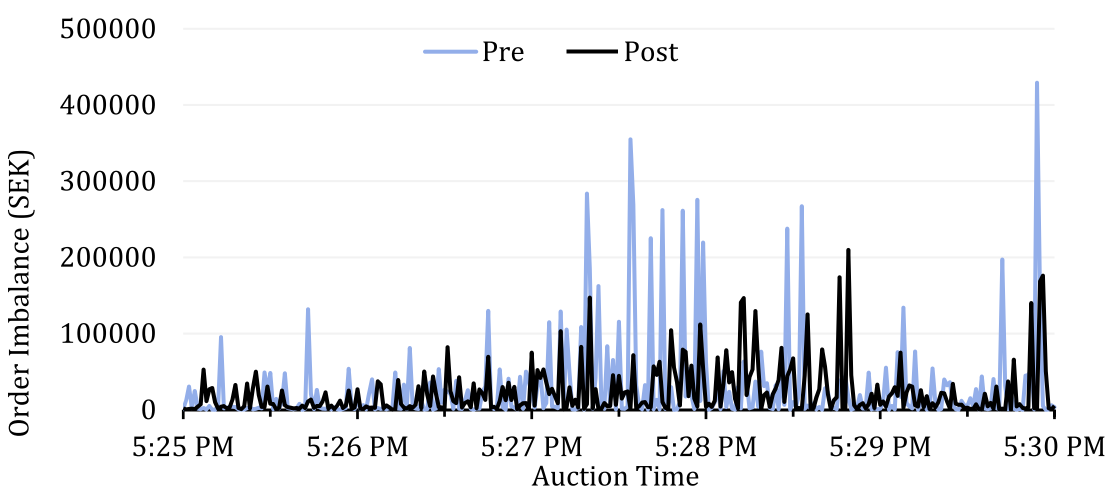
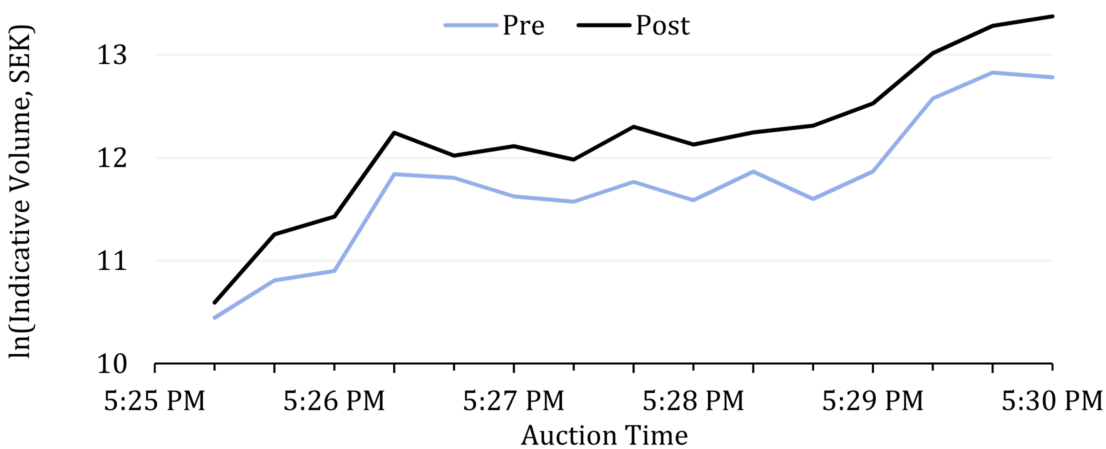


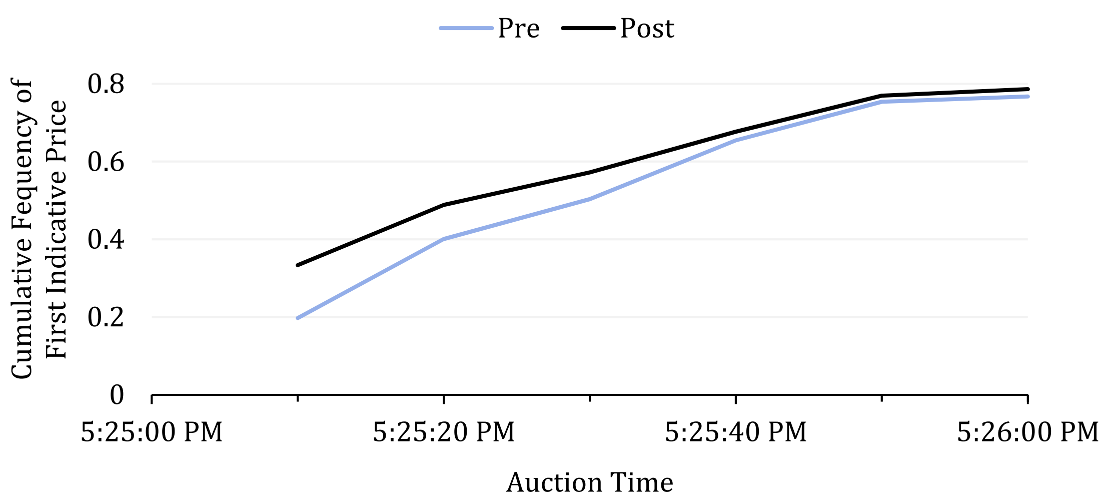
Figure 3. Measures of Auction Attractiveness

This figure reports auction attractiveness measured during the batching period of the closing call auction. Panel A depicts the log SEK *Indicative Volume* at a 20-second frequency for the period 5:25 PM to 5:30 PM. The measure is averaged across stock–days for small- and mid-cap stocks at NASDAQ Stockholm. Panel B shows the cumulative frequency of the time of the first indicative price. The time series has a 10-second frequency for the first minute of the batching period. The pre-event period (*Pre*) contains all trading days from June 1 to November 30, 2014. The post-event period (*Post*) contains all trading days from December 1, 2014, to May 31, 2015.

Panel A: Indicative Volume



Panel B: Closing Auction Cumulative Frequency of the First Indicative Price



Appendix: Volatility bands

Table A1 depicts the volatility thresholds applied to the different stock categories at the opening and closing call auctions for the NASDAQ Nordic segments that are of interest for this study.

[INSERT TABLE A1 HERE]

The CAVE is triggered when the uncross price deviates from the reference price by more than a prespecified threshold. The reference price is the closing price of the previous trading day for the opening call auction and the price of the last trade during the continuous trading session for the closing call auction. The threshold depends on stock-specific characteristics (e.g., whether the stock is a penny share, the liquidity group it belongs to, whether it is a First North stock). Exceptionally, NASDAQ Nordic may readjust the thresholds when required.

Next, as an example, we present the procedure we follow to determine the threshold to apply for each stock and whether the volatility extension should be triggered. Table A2 contains a snapshot of the last minutes of trading for two stocks: the mid-cap THULE.ST in Panel A and the small-cap RABTb.ST in Panel B. Both stocks have a default threshold of 5%. Since, according to NASDAQ documents, they do not fall in the penny share, First North, or liquidity group C categories, the default threshold applies to them. For THULE.ST, the price of the last trade is SEK 92 and the uncross price is SEK 97. Since the difference in price is greater than the threshold of 5%, the volatility extension is triggered. During the auction extension, new orders are submitted and the final price is set at SEK 94, which is below the threshold. For RABTb.ST, the price of the last trade is SEK 4.26 and the uncross price is SEK 4.52. Since the difference in price is greater than the threshold of 5%, the auction extension is triggered. During the extension, traders do not submit new orders or modify existing ones. The auction is executed at the price of SEK 4.52.

[INSERT TABLE A2 HERE]

Table A1. Volatility Bands for NASDAQ Nordic Segments

This table summarizes, for different stock categories, the volatility thresholds determining when the call auction extension is triggered for NASDAQ Stockholm, Helsinki, and Copenhagen. Note that Copenhagen and Helsinki only have volatility extensions implemented during the opening call auction. The technical details presented here are based on the NASDAQ Nordic market model 2015:03, which contains information on volatility extensions in Appendix U.

Stock Category	*Threshold Opening Auction*	*Threshold Closing Auction*
Main Index Constituents[a]	±6%	±3%
Small Caps, Mid Caps, and Large Caps[b]	±10%	±5%
Illiquid Shares[c]	±20%	±10%
Penny Shares		
0.25 SEK/DKK < price < 5 SEK/DKK or 0.025 EUR < price < 0.5 EUR	±50%	±25%
0.1 SEK/DKK < price < 0.25 SEK/DKK or 0.01 EUR < price < 0.025 EUR	±80%	±40%
0.05 SEK/DKK < price < 0.1 SEK/DKK or 0.005 EUR < price < 0.01 EUR	±100%	±50%
0 SEK/DKK < price <0.05 SEK/DKK or 0 EUR < price < 0.005 EUR	±200%	±100%

[a] The main index constituents are OMXS30, OMXH25, and OMXC20 for Stockholm, Helsinki and Copenhagen, respectively.

[b] Excluding the main index constituents, Liquidity Group C shares, and penny shares.

[c] As defined by NASDAQ Nordic (2014b) Liquidity Group C shares. A stock is listed in this category when, the previous month, it traded less than 50% of the days, its average daily turnover was below SEK/DKK 200,000 (or EUR 20,000), or its average spread was greater than 5%.

Table A2. Example of Volatility Extension

This table shows two examples of volatility extensions for the mid-cap stock THULE.ST in Panel A and the small-cap stock RABTb.ST in Panel B. Both stocks fall in the threshold category of 5%. The table is a snapshot of the last minutes of trading for the two stocks. The data are obtained from the Thomson Reuters Tick History database.

Panel A: THULE.ST (February 13, 2015)

Period	*Timestamp*	*Action*	*Price*	*Volume*	*Bid Price*	*Bid Size*	*Ask Price*	*Ask Size*
	5:21:56 PM	Trade	92	492				
LOB	5:21:57 PM	Quote			91.5	734	92	500
	5:24:16 PM	Quote				500		
	5:25:00 PM	Quote			105	30,000	105	29,404
	5:25:00 PM	Indicative price	105	29,404				
	...							
	5:27:59 PM	Quote			104.5		104.5	34,377
	5:27:59 PM	Indicative price	104.5	30,032				
Auction	5:28:24 PM	Quote			99		99	33,792
	5:28:24 PM	Indicative price	99	30,032				
	5:29:34 PM	Quote			97		97	34,920
	5:29:34 PM	Indicative price	97	30,032				
Extension	5:32:48 PM	Quote			94	30,232	94	14,129
	5:32:51 PM	Trade	94	14,129				

Panel B: RABTb.ST (December 17, 2014)

Period	*Timestamp*	*Action*	*Price*	*Volume*	*Bid Price*	*Bid Size*	*Ask Price*	*Ask Size*
LOB	17:21:04	Trade	4.26	3,540				
	17:21:04	Quote			4.26	124		
	17:25:00	Quote				8,540		
Auction	17:26:53	Quote			4.52	50		
	17:26:53	Indicative price	4.52	50				
Extension	17:32:41	Trade	4.52	50				