Not Too Big, Not Too Small? Towards an Optimal Tick Size

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Abstract

Emerging theoretical literature identifies various channels through which tick size changes impact market quality, suggesting that optimal tick sizes balance excessive undercutting with long queues. We test these propositions empirically by simultaneously observing both increases and decreases in tick sizes for cryptocurrencies on the same exchange, while controlling for trading of these assets on competing venues. We show that spread-constrained assets exhibit the most significant changes in market quality, with the largest increases (decreases) in spread and depth when tick sizes are raised (reduced). These assets also experience the most order flow migration, moving away from (towards) the trading venue with tick size increases (decreases). This suggests that mechanical and layering channels dominate within exchanges, while the migration channel also matters across different exchanges. Unconstrained assets do not generally show significant changes in market quality, indicating undercutting is a weaker transmission channel. Beneficial tick size changes are more pronounced on dominant exchanges, while detrimental changes are more evident on fragmented exchanges.

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1 Introduction

Global markets are becoming increasingly competitive with a proliferation of trading venues causing unprecedented levels of fragmentation. Tick sizes, the minimum price increments by which instruments can be traded, have generally been subject to market regulations, preventing equity exchanges from competing directly on this dimension of market structure.[1] However, in the unregulated and highly fragmented realm of cryptocurrency markets, superior market quality is one of the main draw cards to attract liquidity. Here, tick sizes have become one of the major battlegrounds on which exchanges compete for orderflow.

Cryptocurrencies are traded on over 200 global exchanges without any central regulation. This has allowed increasing divergence and heterogeneity in market pricing, structures, and, importantly for our study, tick sizes. The coexistence of various tick sizes and, critically, the observation of modifications (increases and decreases) to these tick sizes across different competing cryptocurrency exchanges allows us to use this emerging market as a laboratory to test several recent theoretical models of the relationship between changes in tick size and market quality, including Werner et al. (2023) and Graziani and Rindi (2023).

Werner et al. (2023) consider a public limit order book (PLB) analagous to a continuous double auction market and derive the effects of a tick-size change as a combination of four different channels of transmission. First, the ability of traders to undercut (or penny) existing standing limit orders ('undercutting effect'), and the cost of doing so. Second, the queuing or dispersion of limit orders at the best bid-ask quotes ('layering effect'). Third, the mechanical increase or reduction in the quoted spread, which cannot be smaller than the tick size ('mechanical effect'). And lastly, the migration of order flow associated with tick size changes to/from other exchanges ('migration effect').

Importantly, they demonstrate that the relative importance of these channels depends on the level of liquidity of the underlying asset. Graziani and Rindi (2023) establish that when investors arrive sequentially and supply liquidity by undercutting or queuing behind existing limit orders, the optimal tick size is a positive function of the asset value and a negative function of stock liquidity. Consequently, the tick size needs to optimally balance investors' choice between liquidity demand and supply by mitigating the inefficiencies created by excessive undercutting and queuing.

While numerous studies have empirically tested individual theoretical predictions from these models (see, for example, O'Hara et al., 2019; Dyhrberg et al., 2023; Foley et al., 2023b;

[1]Foley, Meling and Odegaard (2023) document one of the rare instances of explicit tick size competition in traditional financial markets.

Graziani and Rindi, 2023; Werner et al., 2023), they have not been tested jointly in a multi-exchange framework, where investors can choose between competing trading venues. This is because the existence of numerous assets trading across multiple markets with competing tick sizes is rarely observable in traditional financial assets. The pricing grids on most equity exchanges are typically too coarse and economically significant to clearly observe the undercutting effect (Dyhrberg et al., 2023), while regulator-mandated minimum tick sizes generally prevent exchanges from competing by altering the tick size (Foley et al., 2023b).

Similar to Dyhrberg et al. (2023), we focus on cryptocurrency markets, as the tick sizes in these markets are orders of magnitude smaller than in other markets, which allows for clear delineation of assets by liquidity between tick constrained and unconstrained assets. Existing literature suggests that the intrinsic value of cryptocurrencies is ambiguous, largely constraining price formation to information in order flow (Cheah and Fry, 2015; Dyhrberg et al., 2018). Small tick sizes, combined with the absence of a clear fundamental value, are likely to attract undercutting traders who generally do not have strong view on the fundamental value but, rather, trade opportunistically to profit from small deviations in price (Buti et al., 2015). This enables us to identify undercutting effects more clearly. Since cryptocurrencies are fully fungible and easily traded across numerous exchanges, we can also analyze the migration of order flow across competing venues due to tick size changes. Unlike previous studies constrained by a limited number of listed currency pairs, our empirical setting includes hundreds of currency pairs. While Dyhrberg et al. (2023) limit their high-frequency order-level data analysis to six currency pairs, we identify 420 tick size increasing events and 434 tick size decreasing events across seven cryptocurrency exchanges, with many occurring simultaneously. This allows us to robustly test all empirical predictions of the Werner et al. (2023) model and examine how changes in tick size, both increases and decreases, affect the market quality of liquid and illiquid assets, while also identifying order flow migration across different exchanges.

Our findings confirm that undercutting is detrimental to liquidity provision but leads to increased trading volume. Following theoretical literature, we then separate increasing and decreasing tick size events by liquidity to assess the impact of the binding nature of the tick size.

We show that increasing tick sizes for highly liquid assets leads to a statistically significant increase in quoted, effective and realized spreads, while a tick size increase in illiquid stocks is associated with a statistically significant reduction in those measures. Depth and short-term volatility increases for both liquid and illiquid pairs. The results for tick size decreasing events show a decrease in all measures of spread along with a decrease in depth and short-term volatility for highly liquid pairs and largely insignificant results for illiquid pairs. These findings are generally consistent with theory and provide the most comprehensive empirical tests of the Werner et al. (2023) model.

To better understand how the effect of a tick size change is affected by liquidity, we also separate pairs into three groups based on liquidity before and after the tick size change. We find that during tick size increasing events, spread measures for pairs with unconstrained tick sizes before the event narrow if tick sizes remain unconstrained after the change, but remain unchanged if spreads become constrained following the tick size change. For tick size decreasing events, we show that spreads that remain constrained both before and after the tick size change exhibit the largest reductions. These findings underscore that the contribution of each transmission channel to the overall outcome is highly dependent on the initial and final level of tick constraint.

Finally, as we are able to observe the same currency pairs traded on different exchanges with heterogeneous tick sizes, we provide novel evidence testing the 'migration effect' in a dual PLB market proposed by Werner et al. (2023). We find that increasing tick sizes typically results in migration of volume to competing exchanges and increasing tick sizes has the opposite effect but interestingly, this is not as dependent on the liquidity of the underlying currency pairs. For spread-constrained assets, dominant exchanges benefit more from tick size reductions, showing larger decreases in spreads, smaller decreases in depth, and greater inflow. In contrast, fragmented exchanges suffer more from tick size increases, with larger spread widening, smaller depth increases, and greater outflow. This indicates that beneficial tick size changes are more pronounced on dominant exchanges, while detrimental changes are more evident on fragmented exchanges.

Our study contributes to the burgeoning empirical literature on the relationship between changes in tick size and market quality by being able to analyze concurrent increases and decreases in tick sizes at the same trading venues while simultaneously controlling for the trading of these assets at competing venues.

The remaining sections are structured as follows: Section 2 presents the literature and hypotheses development. Section 3 outlines the data used in the study and provides descriptive statistics. Section 4 reports the empirical results, and Section 5 concludes.

2 Hypotheses development

A significant body of existing literature has documented how historical tick size reductions have improved market quality. The rise of electronic trading and automation led to a rapid increase in trading volume and liquidity at exchanges throughout the 1980s and 1990s, causing tick sizes for many stocks to become more restricted. Harris (1994) shows that by 1989, 45% of all NYSE stock quotations were constrained by the tick size. Increasing execution times intensified competition among exchanges to attract investors seeking liquidity by lowering the trading cost of crossing the bid-ask spread with a smaller tick size. Much of the earlier empirical literature examines these progressive decreases in tick sizes, examining Canada in 1996 (Bacidore, 1997; Porter and Weaver, 1997) and the US in 1992 (Ahn et al., 1996) and in 1997, where they decreased from one-eighth to one-sixteenth of a dollar (Goldstein and Kavajecz, 2000). Tick sizes eventually reduced to multiples of one penny with decimalization in 2000-2001 (Bessembinder, 2003; Chung et al., 2004).

These earlier studies revealed that reducing tick sizes resulted in a decline in various spread measures, especially in stocks where the tick size was frequently binding (Chung et al., 2004). However, the benefit for smaller, less liquid stocks was ambiguous and in some cases detrimental. Moreover, narrower spreads generally reduced the depth at the inside quotes (Porter and Weaver, 1997; Goldstein and Kavajecz, 2000; Bessembinder, 2003; Chung et al., 2004). Since institutional investors prefer larger tick sizes than retail investors Seppi (1997), narrower spreads did not significantly alter the trading costs of institutions (Eaton et al., 2021). European studies have also yielded inconclusive results, as both increases and decreases in tick sizes neither reduced liquidity provision for large trades nor changed the quoted spreads (Bourghelle and Declerck, 2004). In response, the US Securities & Exchange Commission (SEC) established the ”Tick Size Pilot Program” in 2015 to evaluate whether widening the tick size could benefit smaller, less liquid stocks.[2]

The results of the US Tick Size Pilot, however, are similarly inconclusive. Griffith and Roseman (2019) find that market quality decreases for stocks where the tick size increase is binding and remains largely unchanged for stocks with a non-binding tick-size. Chung et al. (2020) find that execution cost of small orders increases with both quoted and effective spreads rising. By contrast, the cumulative depth and the price impact of large orders improves. These studies suggest that solving for the optimal tick requires a more complex optimization, a result which is corroborated by the emergence of theoretical literature on the topic. Werner et al. (2023) construct a theoretical model that identifies multiple differ-

[2] Similar studies were carried out in the European markets under the minimum tick-size regime introduced by Article 49 of MiFID II. (see, for example, Foley et al., 2023b).

ent channels of transmission. Their model shows that in a non-fragmented market, a tick size change generates three main effects - with their relative importance determined by the liquidity level of the underlying asset. Assuming a tick size decrease, firstly, undercutting becomes cheaper as gaining price priority through a limit order sacrifices a smaller price improvement. Higher prevalence of undercutting lowers the probability of order execution and thus decreases traders' willingness to supply liquidity through limit orders. The 'undercutting effect' is amplified in illiquid assets, where there are more 'free ticks' inside the spread and thus more opportunity for traders to undercut the existing quotes.

Secondly, limit orders that were previously clustered at a limited number of price levels now disperse across a large number of price levels due to the finer pricing grid. Consequently, traders willing to post limit orders have a higher probability of gaining front queue positions at these new price levels. Unlike the undercutting effect, this incentivizes liquidity provision. This 'layering effect' is most pronounced in liquid markets with many traders ready to provide liquidity, who would otherwise create long queues of limit orders at the best quotes on the larger tick PLB.

Finally, a smaller tick size mechanically reduces the inside spread. For traders deciding whether to post a market or a limit order at the top of the book, a narrower spread lowers the opportunity cost of switching from a limit to a market order, thus increasing their incentives to take liquidity. This 'mechanical effect' is strongest for liquid stock, where trading is concentrated at the first level of the book and the inside spread is binding. Conversely, it is weakest for illiquid stocks, as limit orders do not generally cluster at the smallest possible price increment.

Combining these three effects in an unfragmented market, the Werner et al. (2023) model shows that a decrease in tick size generates a mechanical decrease in the inside spread and increases the layering of limit orders across multiple price steps. These two effects dominate the undercutting effect for liquid stocks, making investors more inclined to supply liquidity rather than take it. This results in an improvement in spread but a deterioration in depth and volume. In illiquid stocks, where there are more free ticks between the inside spread, tick size decreases strongly promote undercutting. This disincentivizes investors to offer liquidity by posting limit orders. Instead, investors are encouraged to take liquidity via market orders by crossing the spread. This leads to an increase in spreads as well as a reduction in depth. However, as this leads to more trading, volume improves.

An increase in tick size reduces layering, with quotes clustered across fewer price steps. For liquid stocks, there is a mechanical increase in spread and an increase in depth. The opportunity to undercut existing quotes in this situation becomes difficult as spreads frequently become binding. As time priority gains importance, execution time increases and investors prefer to take rather than provide liquidity. This incentivizes traders to cross the spread and leads to increased volumes. For illiquid stocks, the risk of undercutting decreases as price steps widen and become economically significant. Reductions in undercutting increase the probability of execution, incentivizing traders to provide (rather than take) liquidity by crossing the spread. This leads to an improvement in spreads and increases in depth. However, greater liquidity provision – instead of higher trading activity – decreases volume. The interaction of these three effects during a tick size changes thus leads to a number of testable hypotheses.

Hypothesis 1. An increase in tick size for tick-constrained assets leads to an increase in spreads, increase in depth at the inside quotes and increases in traded volumes.

Hypothesis 2. An increase in tick size for tick-unconstrained assets leads to a decrease in spreads, increase in depth at the inside quotes and an decrease in traded volume.

and

Hypothesis 3. A decrease in tick size for tick-constrained assets leads to a decrease in spreads, decrease in depth at the inside quotes and decrease in traded volume.

Hypothesis 4. A decrease in tick size for tick-unconstrained assets leads to an increase in spreads, decrease in depth at the inside quotes and increase in traded volume.

An extension of the Werner et al. (2023) theoretical model explores a dual market in which a PLB competes with a transparent Crossing Network (CN) that enforces priority and continuously executes orders at the midpoint of the bid and ask prices. In this setting, the authors identify a fourth transmission channel and demonstrate that within a competitive framework, the 'migration channel' may alter the effects of a tick size change from what is observed in a single market. They find that competition generally increases the migration of order flows to that venue, leading to an overall deterioration in market quality. A smaller tick size is associated with a deterioration in the PLB of both liquidity supplied and demanded, resulting in reduced market quality. Deep books intensify the migration effect, because the intense competition for liquidity supply strengthens the incentives for impatient traders to jump the queue and gain execution priority by switching to the CN, where limit orders are instantly matched and executed at the midquote. Therefore, similar to the layering and mechanical effects, the migration effect is more evident in liquid stocks. They show that in a fragmented market, the significant migration of both aggressive limit and market orders to the CN for liquid stocks confirms the negative impacts on depth and volume observed in a non-fragmented market. Interestingly, the strong migration effect offsets the layering effect, decreasing liquidity provision and slightly worsening the spread. For illiquid stocks, the strong undercutting effect combines with the migration effect, negatively impacting both spreads and depth, as well as causing a decline in volume. Furthermore, their model shows that when taking into consideration the migration effect, which is magnified in deep books, all observed results are stronger for liquid stocks compared to illiquid stocks.

However, Werner et al. (2023) note that price competition in a CN is very aggressive, and thus represents an upper limit of potential migration to a rival exchange following a tick size change. Thus, the effect is anticipated to be weaker with a competing PLB. The authors suggest that it may even revert, with market orders moving to the cheaper PLB that has reduced its tick size. This is supported empirically by Foley et al. (2023b), who explore the effects of tick size changes on European trading venues, findng that venues which reduced their tick size immediately gained market share in both quoted and executed volumes from exchanges that maintained larger tick sizes. In contrast, Ahn et al. (1998) do not observe a migration in order flow from the US to the Toronto Stock Exchange (TSE) for stocks cross-listed on US exchanges, following the reduction in tick size on the TSE. Consequently, the direction and magnitude of changes in market quality metrics are likely a function of the intensity of the migration effect, which is a combination of the underlying liquidity and the relative differences in tick sizes between the completing exchanges. Our setting considers two competing PLBs and approximates the intensity of competition by the difference in the tick size between the exchange undergoing the tick size change and a competing venue, examining liquid and illiquid assets separately. This leads to our final set of hypotheses.

Hypothesis 5. An increase in tick size for tick-constrained assets leads to a migration in volume to other exchanges.

Hypothesis 6 An increase in tick size for tick-unconstrained assets leads to a migration in volume from other exchanges.

and

Hypothesis 7. A decrease in tick size for tick-constrained assets leads to a migration in volume from other exchanges.

Hypothesis 8. A decrease in tick size for tick-unconstrained assets leads to a migration in volume to other exchanges.

3 Data and Summary Statistics

This section details the sample assets and data sources used in our research on the effects of tick size changes within the treated exchanges. It includes the definition of the variables, as well as the descriptive statistics for the undercutting runs, liquidity provision, and market quality.

3.1 Data Sources and Sample Selection

We gather tick-level trade and quote data from the Tardis[3] database for assets, covering three weeks before and after the tick size change. Tardis provides data on all individual trades and snapshots of the top of the PLB (best bid/ask) whenever there is a change. The data are recorded in UTC and time-stamped to milliseconds, and in some cases, even microseconds. Since Tardis does not classify trade direction, we apply the Lee and Ready (1991) algorithm to infer the trade side. These high-frequency trades and quotes data help us construct the undercutting run matrix for the treated assets and examine the effects of tick size changes on market quality. We manually collect all tick size change announcements for major exchanges with high daily trading volumes, including OKX Spot, Binance Spot, KuCoin Spot, Kraken, Coinbase and Binance US. These six exchanges represent around 26% of the daily trading volume across all 669 cryptocurrency exchanges listed on coinmarketcap.[4] As the matching engines of cryptocurrency exchanges can affect the computation of various liquidity and trading metrics, we check the precision and speed of the matching engine using the identification framework proposed by Foley et al. (2023a). Detailed analysis of the precision and speed of each exchange is outlined in Appendix A. Our evaluation reveals that, among all exchanges examined, only Kraken lacks a fast matching engine. To address this issue, we choose a 2-millisecond time window to aggregate Kraken's trade data for 2021 and 2022. Following an update to their matching engine in 2023, we use a 200-microsecond time window.

[Insert Table 1 here]

Table 1 reports the tick size change events and samples, with a more detailed sample selection provided in Appendix B. We limit our analysis to events where at least 30 cryptocurrency pairs (assets) underwent a tick-size change. We then apply a liquidity filter to each event, and exclude assets with fewer than 200 average daily trades, those lacking pre-change

[3]Tardis data accessed through https://www.cryptodatawarehouse.org/.

[4]coinmarketcap.com, September, 2023

and post-change data or those with unbalanced panels. Although cryptocurrency exchange announcements usually accurately identify tick-size changes, we validate each change by estimating the daily minimum and mode of bid (ask) price movements for all listed assets based on quote data.

The tick size verification process flags any discrepancies between the announced and actual tick size changes. For example, tick size changes confounded with other events, unreported events, and events that did not occur despite being flagged in the announcement. We list these unverified events for all assets in Table A.2 and exclude these anomalies from our sample. Our filtering process yields a final sample of 420 assets across six tick size increase events and 434 assets across seven tick size decrease events. For our regression analysis, we construct a sample of controlled assets that have the same initial tick size and comparable daily trading volumes but did not undergo a tick size change. Cryptocurrencies can list on multiple exchanges, and asset's tick size may change on one exchange but remain the same on others. Panel B of Table 1 shows the number of assets experiencing tick size increases or decreases that can be matched with assets on other exchanges where tick sizes remain unchanged. For consistency, we use the same tick size estimation verification process described above on the matched sample to identify any potentially confounding effects.

3.2 Variable Measurement

We use the Tardis trade-and-quote data to construct the standard measures of market quality, including the quoted spread, effective spread, realized spread, trading volume, depth at inside spread and short-term volatility. To construct the variables for undercutting runs, liquidity provision, market quality and control variables we follow the methodology outlined in Dyhrberg et al. (2023).

3.2.1 Undercutting Runs Measures

Undercutting is generally defined as a sequence of limit orders placed within the highest bid or lowest ask quotes on the same side of the order book, involving price improvements that are economically insignificant. Dyhrberg et al. (2023) define price improvement in an undercutting run as being less than one cent, based on the minimum pricing increment on many equity exchanges. In our setting, we explore a significantly more heterogeneous sample of assets, some of which have relatively large tick sizes and high prices. Since the minimum price improvement for these assets can exceed one cent, we have adjusted our definition of undercutting by applying different price increment thresholds for assets linked to fiat-like currencies and cryptocurrencies.[5] For assets pegged to the US dollar including USDT, USDC, USDP, and BUSD, the threshold is set to the greater of either five times the larger tick size (measured before and after the tick size change) or one cent. For assets based on other cryptocurrencies, including ETH, BTC, etc., the threshold is five times the larger tick size. In our setting, the undercutting run in the bid price sequence begins with two small price improvements that are below the undercutting threshold. A run continues if it is interrupted by a single order cancellation and the price reverts to or stays above the previous bid price. An undercutting run ends under four conditions: a) the market order is executed, indicated by the quote price being interrupted by the trade price, b) two consecutive cancellations occur, c) a single cancellation causes a price movement in the opposite direction that exceeds the previous quote, and d) the price movement exceeds the undercutting threshold.

For each undercutting run, we construct six measures to illustrate the duration, process and result of undercutting runs. *Number of runs* represents the number of runs within a 15-minute window that begin with at least two undercuts. We also report the total number of undercutting runs (in thousands) as *Undercutting run groups* and the proportion of one-tick-size undercuts within each run, *One tick undercuts(%)*. *Step size ($)* is the mean USD price improvements of each undercut per run. *Step size (post ticks)* is the mean post tick size movement of each undercut per run. The *Step size* measures depict the magnitude of each undercut. *Price difference (bps)* is the average price difference between the beginning and end of the run, measured in bps. We define the *Price difference (bps)* as:

$$Price\ difference = \frac{Price_{end} - Price_{beginning}}{Price_{beginning}} \times 10,000 \tag{1}$$

where $Price_{end}$ is the bid price or ask price at the end of the undercutting run, $Price_{beginning}$ is the bid or ask price at the beginning of the undercutting run.

Price difference (post ticks) is the average price difference between the beginning and the end of the run, measured in post ticks. *Run duration (seconds)* is the duration of undercutting run in seconds. *Seconds between trades* is the number of seconds between trades.

[5]For example, the tick size of AAVEBUSD traded on Binance rose from 0.01 to 0.1 BUSD on August 26, 2021. Since the value of BUSDUSD is approximately $1, this implies that the minimum price improvement for AAVEBUSD in a limit order is around 10 cents after the tick size increase.

3.2.2 Liquidity Provision Measures

We construct four measures to illustrate liquidity provision in limit order books and calculate the average of these variables every 15 minutes. *Order exposure (seconds)* is the duration of the best bid or ask. *Average order exposure (seconds)* is calculated as the mean exposure of the best bid or ask every 15 minutes. *Spread duration (seconds)* is the duration of each quoted spread. It is measured for every quote record as the best bid and ask update, facilitating the plotting the relationship between *Quoted spread (bps)* and *Spread duration. Average price steps* and *Resting limit orders* are constructed to illustrate the composition of one market order. The aggregation of the executed limit order to one market order is explained in more details in Appendix A.

Price steps are estimated as the number of price levels included in each market order. Subsequently, we calculate the *Average price steps* as the average number of price steps a market order consumes in a 15-minute interval. *Resting limit orders* is the average number of limit orders resting at the same price step in a 15-minute interval. We estimate the number of resting limit orders for the market orders with more than one price step by excluding the last price level for each market order. Then we count the number of resting limit orders for each price step and calculate the average for the number of resting limit orders for each price step in a 15-minute interval.

3.2.3 Market Quality Measures

We construct three measures of trading cost, along with one measure for depth at best, trading volume and short-term volatility. We calculate the relative quoted spread to assess the cost of providing a marginal dollar of liquidity. We define the *Quoted spread(bps)* as the relative quoted spread:

$$Quoted\ spread_{it}(bps) = \frac{Ask_{it} - Bid_{it}}{m_{it}} \tag{2}$$

where Ask_{it} and Bid_{it} are the best ask and bid quotes at time t for asset i, the midpoint m_{it} at time t is:

$$\frac{Ask_{it} + Bid_{it}}{2} \tag{3}$$

Then we measure the time-weighted *Quoted spread$_{it}$(bps)* in a 15-minute interval. We define the quoted spread, measured in current tick, as:

$$Quoted\ spread_{it}(tick) = \frac{Ask_{it} - Bid_{it}}{current\ tick_{it}} \tag{4}$$

where if the date is earlier than the event day, the quoted spread is measured in pre-tick. If the date is later than the event day, the quoted spread is divided by the new tick. The *Quoted spread*$_{it}$*(tick)* can reveal the leeway of the spread in pre and post period. Then we estimate the time-weighted *Quoted spread*$_{it}$*(tick)* in a 15-minute interval.

We introduce the effective spread by matching the best quotes prior to the trade with the executed trade price and measure the actual trading costs. The effective spread, measured in bps, is defined as:

$$Effective\ spread_{it}(bps) = \frac{2q_{it}(P_{it} - m_{it})}{m_{it}} \tag{5}$$

where $2q_{it}$ is the direction of the trade, taking $+1(-1)$ for a buyer (seller) initiated order and P_{it} is the price of the trade at time t for asset i. Then we estimate the volume-weighted *Effective spread*$_{it}$*(bps)* in a 15-minute interval.

For estimating the liquidity supplies' gross profits at a given time window, the realized spread ,measured in bps, is as follows:

$$Realized\ spread_{it}(bps) = \frac{2q_{it}(P_{it} - m_{it+Xs})}{m_{it}} \tag{6}$$

Where Xs is the time horizon for the midpoint of interest. Following the methodology of Dyhrberg et al. (2023) and Foley et al. (2023b), we use uniform $30s$ and $60s$ as X-second time horizons across all assets.[6] We estimate the volume-weighted *Realized spread*$_{it}$*(bps)* in a 15-minute interval. We measure *Depth* in \$1,000 as the dollar volume quoted at the best prices. We estimate the time-weighted *Depth* in a 15-minute interval. The *Volume* is defined as the 15-minute total trading volume in \$100,000. The volume for each trade is obtained by multiplying the price by the amount and then converting it to USD. *Short-term volatility* is the volatility of midpoint-to-midpoint returns, calculated every 15 minutes and measured in bps. In line with Rzayev and Ibikunle (2019), it is computed as the standard deviation of midpoint-to-midpoint returns in a 15-minute interval. Each midpoint is calculated based on the best bid and ask quotes corresponding to one second in a 15-min interval.

[6] We also use $10s$ as X-second time horizons. The results are similar.

3.2.4 Control Variables

Following Dyhrberg et al. (2023), we select volatility and number of trades as control variables. *Volatility* is estimated as the currency-time high-low price range scaled by the high-low midpoint in percent. The minimum and maximum prices are derived from the trade data within each 15-minute interval. *Trades* is the number of trades in a 15-minute interval.

3.3 Descriptive Statistics

Table 2 provides a statistical summary of the effects of tick size changes on undercutting runs and liquidity provision, aggregated across the six increasing and seven decreasing events, respectively. Panel A shows the duration and consequences of undercutting runs. Following a tick size increase, the number of undercutting run groups drops by 76.93%, while it rises by 787.28% after a tick size decrease. For assets with increasing tick sizes, the number of runs in 15 minutes reduces from 198.97 to 51.11. Conversely, for assets with decreasing tick sizes, it rises from 22.17 to 94.74. A larger tick size incentivizes liquidity providers to undercut by one tick, as evidenced by its increase from 63.43% to 74.90% following a tick size increase, and its decrease from 90.36% to 65.02% after a tick size decrease. The step size of undercuts, measured in USD, becomes more economically significant after tick size increases (a 154.34% increase) and less significant after tick size decreases (a 60.45% decrease). Due to undercutting runs, the price difference in bps rises by 75.50% after a tick size increase and falls by 53.51% after a tick size decrease. The ratio of undercutting duration to the seconds between trades rises from 3.42% to 5.10% for assets with increasing tick sizes and falls from 2.10% to 1.67% for for assets with decreasing tick sizes. This indicates that with an increase in tick size, quotes are more likely to converge to the true spread before the trades are executed. Conversely, with a decrease in tick size, trades are more likely to occur before the undercutting runs are completed.

[Insert Table 2 here]

Panel B in Table 2 illustrates the impact of changes in tick size on liquidity provision. Following an increase in tick size, the resting time for limit orders lengthens from 14.32 seconds to 40.13 seconds, an increase of 180.23%. This is accompanied by an 8.47% reduction in the average market order price step and a 59.94% rise in the number of resting limit orders. Conversely, treated assets experiencing a tick size decrease see their average order exposure time fall from 178.89 seconds to 79.72 seconds. The average price steps increase by 15.92%, and the number of resting limit orders at each price level drops by 42.13%. These results imply that an increase in tick size encourages traders to provide liquidity, whereas a decrease in tick size motivates traders to undercut due to the lower cost.

[Insert Figure 1 here]

To demonstrate the impact of changes in tick size on liquidity provision, the heatmap in Figure 1 illustrates the duration of the relative quoted spread in bps, along with its frequency distribution for tick size increase and decrease. Panel A shows that before the tick size increase, most observed spreads lasted less than 25 seconds. It is evident that narrower quoted spreads (under 75 bps) persist for a longer duration. This contrasts with findings of Dyhrberg et al. (2023), which suggest that spread duration is relatively independent of spread size. We attribute this difference to the distinct samples used. Our study examines 420 currency pairs with increasing tick sizes across six events, whereas their study involved six currency pairs during a single tick size increase event on Kraken. Compared to the mean time-weighted quoted spread of 67.87 bps in the pre-period and 47.6 bps in the post-period reported by Dyhrberg et al. (2023), our tick size increase samples show a more constrained spread. The pre-period mean is 22.04 bps, and the post-period mean is 20.93 bps. The constrained spread prevents undercutting, resulting in quotes lasting longer within the narrower spread. Following the tick size increase, spreads become even more constrained, as depicted in (b) After. Observations cluster within the narrower spread range of 25 bps. These constrained spreads occur more often, and last longer than 75 seconds.

Panel B illustrates the relationship for tick size decreases. Spreads within five bps range typically last for less than 10 seconds. As the spread increases, the duration distribution widens, with spreads between 10 and 40 bps more likely to persist for 10 to 75 seconds. Spreads exceeding 100 bps still often persist for over 25 to 60 seconds. This variability is attributed to the moderate tick size and lack of undercutting in the market (with a mean of number of 22.17 runs before the tick size decrease), leading to a random distribution of durations across different spreads. After the tick size decrease, the prevalence of undercutting causes most spreads larger than 100 bps last only 4 seconds. As undercutting continues and spreads narrow, observations cluster with a more evenly distributed duration, forming a smooth bump across the 0-50 bps range. This implies that following a tick size decrease, ongoing undercutting results in narrow spreads persisting for an average of 10 seconds.

[Insert Table 3 here]

Table 3 documents the impact of tick size changes on market quality. Notably, for assets with both increasing and decreasing tick sizes, there is a consistent reduction in quoted spread, effective spread, and realized spread, although the magnitudes vary. For assets with tick size increasing, the quoted spread, effective spread and realized spread in 30 seconds all decrease, with declines of 5.03%, 3.20% and 20.07% respectively. For assets undergoing tick size decreases, these three spreads experience reductions of 22.51%, 11.52%, and 15.14%, respectively. Figure 2 illustrates the shift in spreads and tick sizes, depicting the relationship between the average relative tick in bps and the average time-weighted quoted spread in bps before and after the event. Panel A shows assets with an increasing tick size. In the pre-period, most assets have a relative tick below 2.5 bps, with most spreads within 40 bps. After the increase in tick size, the relative spread rises to between 1 and 7.5 bps, with majority of spreads clustering below 20 bps. After the tick size increase, more observations aligning with the y = x line, indicating that the relative tick equals the relative quoted spread, and spreads are binding. In Panel B, we observe the opposite effect, with the distribution of observations changing from widely dispersed to more clustered. Before the tick size decreases, the tick size for most treated assets falls within the range of 0-30 bps, with spreads lower than 80 bps. Following the tick size decrease, the observations converge within a 5 bps range of relative tick and a 60 bps spread range.

[Insert Figure 2 here]

Table 3 highlights the distinct impact of tick size increases and decreases on depth at best and short-term volatility. Following an increase in tick size, the depth at the best improves significantly by 195.60% (rising from $4,308 to $12,733), whereas for assets with a decreased tick size, the depth decreases by 67.40% (falling from $3,312 to $1,080). This implies that a larger tick size can enhance liquidity provision, while a smaller tick size scatters orders across more price levels, reducing inside depth. Short-term volatility rises by 24.96% after the tick size increase and falls by 15.98% following a tick size reduction. However, after either tick size change, trading volume rises by 8.96% and 74.62%, respectively. Considering the differing impact on the number of trades in 15-minute intervals, there is a 5.50% decline after tick size increases and a 45.81% increase after tick size decreases. This suggests that the increased volume may stem from distinct mechanisms. After tick size increases, each order has higher economic price to be executed than with the old tick size, resulting in a relatively small volume increment. Conversely, with tick size decreases, traders are more willing to take liquidity due to undercutting and mechanical effects, leading to a simultaneous increase in the number of trades and trading volume.

4 Empirical Analysis

4.1 The Impact of Undercutting Runs on Liquidity Provision

For comparison with the results of Dyhrberg et al. (2023), we calculate and report the undercutting metrics using the highly granular high-frequency trade and quote data from Tardis. We regress the liquidity provision metrics on the number of undercutting runs for assets with increasing and decreasing tick sizes to investigate changes in liquidity provision behavior, as depicted by Equation 7. When pooling across all events, the stock identifier i corresponds to the unique Event-Asset combination. This specification allows us to explore how the market quality of the same asset is affected by changes in tick size, separately considering each trading venue.[7]

$$LiquidityProvision_{it} = \alpha_i + \beta_1 Numberofruns_{it} + \beta_2 Trades_{it} + \beta_3 Volatility + \varepsilon_{it} \quad (7)$$

where $LiquidityProvision_{it}$ is a set of measures for liquidity provision, which includes the *Average order exposure*, *Average price steps*, *Number of resting limit orders*, *Depth*, *Volume*, and *Short-term volatility.*

[Insert Table 4 here]

The results in Table 4 show that, consistent with Dyhrberg et al. (2023), increased prevalence of undercutting trading strategies leads to statistically significant reduction in order exposure time, lower number of resting limit orders per price level, and less depth at best. It also leads to an increase in the average price steps consumed by a market order. Building on prior research, our enlarged sample highlights distinct consequences of undercutting runs when comparing tick size increases and decreases. It confirms that undercutting is positively related to volume when the tick size decrease, but negatively correlated to it when tick size increase. This implies that increasing the attractiveness of undercutting discourages liquidity provision, as predicted by Werner et al. (2023). Traders will prefer to consume liquidity rather than provide it when they risk being undercut. To better understand these transmission mechanisms, we separate our sample into assets with increasing and decreasing tick sizes and analyze tick-constrained and unconstrained assets separately.

[7]For example, AVA-BTC traded on the binance-210826 event is distinct from AVA-BTC traded on Kucoin-230118 event.

4.2 The Impact of Tick Size Change on Market Quality

4.2.1 Regression Model

We build on the research of Dyhrberg et al. (2023) and Werner et al. (2023) by employing a difference-in-difference (DiD) framework to investigate the role of tick size changes on market quality. We identify 420 treated assets across six tick size increasing events and 434 treated assets across seven tick size decreasing events. If an increase in tick size results in a decrease in undercutting for treated assets, we anticipate an improvement in market quality compared to unchanged assets. Conversely, if tick size decreases, the resulting increase in undercutting behavior is expected to erode liquidity provision and deteriorate the market quality of the treated assets. The DiD regressions for market quality on tick size changes are specified in Equation 8 below:

$$MQ_{it} = \alpha_i + \beta_1 Post \times Treat + \beta_2 Post + \beta_3 Trades_{it} + \beta_4 Volatility + \varepsilon_{it} \tag{8}$$

where MQ_{it} represents seven different proxies of market quality for event-assets i in a previously defined 15-minute interval t. $Treat$ is an indicator variable identifying the treated assets, and is equal to one for assets with an increasing (or decreasing) tick size and zero for control assets. $Post$ is an indicator variable representing the post-period, set to one after the tick size change and zero before. All control variables are defined in Section 3.2.

Following Dyhrberg et al. (2023), Graziani and Rindi (2023) and Werner et al. (2023), we use tick size constrained assets as proxies for liquid assets and tick size unconstrained assets for illiquid assets, analyzing these conditions separately. To gauge the level of spread constraint for an asset, we develop a continuous measure based on the quoted spread in the current tick. Secondly, we compare the quoted spread in the current tick to five and estimate the ratio of intervals where quoted spread in current tick is less than five across all 15-minute intervals. We employ the ratio value of 80% to determine the cutoffs for different groups with assets classified as 'Constrained' if the ratio exceeds the 80% cutoff, or 'Unconstrained' if the ratio is at or below this threshold. Figure 3 plots a series of histograms to illustrate the cut-off ratios for different groups. Below the 80% threshold, constrained assets constitute 39.89% of the pooled assets, while unconstrained assets account for 60.11%. Panel A in Figure 4 presents the histogram of the constrained ratio for assets with increasing tick size in the pre- and post-period. Following the tick size increase, the share of constrained assets among those with widening tick size rises from 1.90% to 61.90%. Conversely, Panel B in Figure 4 illustrates that the proportion of unconstrained assets among those with narrowing tick size surges by 72.12% after the event.

[Insert Figure 3 here]

[Insert Figure 4 here]

4.2.2 Tick size increase

We begin by analyzing the causal relationship between tick size increases and market quality within exchanges. This analysis considers the effects of undercutting, layering and mechanical influences on both liquid and illiquid assets. Next, we assess the migration effect by comparing samples from exchanges with increased tick sizes to those with unchanged tick sizes. Finally, we explore how market fragmentation induced heterogeneity, has impacted market quality.

Table 5 presents the regression results for tick size constrained and unconstrained assets. Panel A estimates the DiD effect of the interaction term $Treat \times Post$ for treated assets classified as 'Constrained' and 'Unconstrained' by the current tick. The table shows that increasing tick sizes in constrained markets mechanically widens all measures of spread. Quoted spread increases by 5.40 basis points (bps), while effective and realized spread within 30 seconds increase by 6.02 bps and 3.39 bps, respectively. All increases are statistically significant. This finding aligns with theoretical predictions of Werner et al. (2023) and the empirical work of Barardehi et al. (2022). By contrast, in tick-unconstrained markets, spreads either remains unchanged or exhibit statistically significant narrowing. Quoted and effective spreads remain unchanged while realized spread within 30 and 60 seconds decreases by 0.77 bps and 0.61 bps, respectively. While the constrained results are in line with theory, the diverging results for the unconstrained sample suggest that the outcome is dependent on the level of constraint after the tick size increase. Increasing tick sizes for constrained assets is clearly detrimental as it mechanically increases spreads, but for highly unconstrained assets, it may be beneficial to market quality and reduce spreads. In both constrained and unconstrained sample, we find that depth rises as fewer price increments concentrate liquidity on the remaining price steps, as expected. In contrast, we do not observe a large change in trading volume and short-term volatility is positive but not always significant. Aside from volume, these results are consistent with hypothesis 1 but only partially support hypothesis 2.

[Insert Table 5 here]

To better discern how a change in tick size effects liquidity across the different tick constraint levels, we group assets into three possible categories based on both pre and post tick size classification, defining constraint based on the current tick. These are assets transitioning from Unconstrained to Constrained (Uncon2Cons), Unconstrained to Unconstrained (Uncon2Uncon), and Constrained to Constrained (Cons2Cons) spread levels.[8] These results are reported in Panel B. The results show that spread measures narrow for assets that remain in an unconstrained state. Quotes spread falls by 2.72 bps, effective spread declines by 1.91 bps and realized spreads within 30 seconds decreases by 1.89 bps. All coefficients are statistically significant. These findings confirm theoretical predictions that as undercutting becomes more expensive, it will diminish, thereby encouraging investors to provide more liquidity through limit orders. Larger minimum trading increments thus improve spreads, provided assets remain unconstrained and investors do not have to queue after the tick size change. Intuitively, assets that remain unconstrained after the tick size increase have not yet exceeded their optimal tick size level and thus should lead to an overall improvement in market quality metrics as predicted by Werner et al. (2023) and our hypothesis 2. For the 'Uncon2Cons' group, the effect of increasing tick size on spread is mixed as there is no clear theoretical prediction, but depth and short-term volatility increase.

To isolate the transmission channel, the 'Uncon2Cons' category can be further separated to differentiate between assets that become constrained primarily due to a mechanical increase in spread, as the new tick size exceeds the original spread, and those where the spread narrows due to increased liquidity provision. For example, during the Binance event on August 26, 2021, the tick size for MATICUSDT increased from 0.00001 to 0.001. Since the quoted spread before the tick size increase was just 0.257 post-ticks, it mechanically caused the quoted spread to rise from 2.159 bps to 7.153 bps (1.011 post-ticks). Figure 5 investigates these two 'Uncon2Cons' scenarios, using the pre-leeway less than one, two or three post ticks as a measure to separate the mechanical effects from other transmission channels.

[Insert Figure 5 here]

The solid line in Figure 5 represents assets with leeway up to the threshold N before the tick size increase, while the dashed line represents assets with leeway greater than N. Panel A shows a clear increase in spread after the tick size increase for constrained assets on the event date, which progressively weakens as the constraint level is reduced in Panel

[8] Spread-constrained assets that experience an increase in tick size must, by definition, remain constrained after the tick size change. Therefore, the Cons2Cons group is already listed as 'Cons' in Panel A.

B and C. In contrast, assets with pre-leeway larger than those values exhibit a decreasing trend between the panels. This indicates that for assets with sufficient leeway, the quoted spread narrows, while the spread for assets with limited leeway expands. These findings underscore the varied impact of tick size increases on spreads, depending on the initial and final spread constraint states of the treated assets. Based on the evidence from the figures above, we selected post tick thresholds of two to examine the differential effects of pre-leeway thresholds below or above this value. These regression results are presented in Panel C of Table 5. Similar to Figure 5, unconstrained-to-constrained assets with limited pre-leeway (labeled as 'True') capture the mechanical effect, as shown by an increase in spreads. The quoted spread rises by 2.63 bps, and the effective spread increases by 2.55 bps. For assets with a larger pre-leeway (labeled as 'False'), we only observe a slight improvement in spreads, with the realized spread improving by 0.94 bps over 30 seconds due to enhanced liquidity provision. Depth increases for both groups as expected. However, the layering effect is more pronounced for more constrained assets with limited pre-leeway. Volume falls slightly in the constrained sample, while short-term volatility rises in both cases. For robustness, Table A.9 shows a threshold of three post ticks, with results not materially different.

For robustness, Table 6 presents results based on a slightly different subsample analysis of the unconstrained assets from Panel A in Table 5. In this table, groups are denoted as 'A-B', where A represents the constraint level based on the current tick, and B represents the constraint level based on the post-tick. Specifically, 'Uncon-Uncon' refers to assets that remain unconstrained under both the current and post-tick rules, while 'Uncon-Cons' denotes assets that are unconstrained under the current tick rule but become constrained under the post-tick rule. As previously noted, the results for the 'Cons-Cons' group align with the 'Cons' group in Panel A of Table 5. For the 'Uncon-Uncon' group, the results become more pronounced compared to Table 5, with consistent improvement across all spread measures. Specifically, the quoted spread decreases by 3.85 bps, the efficient spread narrows by 2.44 bps, and the realized spreads in 30 and 60 seconds decrease by 2.22 bps and 1.81 bps, respectively. This finding underscores the importance of accurately classifying unconstrained assets by using both pre- and post-tick measures to define the constraint level for tick size increases. Conversely, the 'Uncon-Cons' group exhibits an increase in spread, with quoted and efficient spreads rising by 1.44 bps and 1.61 bps, respectively. This suggests that for assets with increasing tick sizes, defining the constrained level solely based on the current tick may lead to misclassification, as assets may become either constrained or unconstrained after the tick size change. Aside from volume, these results are consistent with both hypothesis 1 and 2.

[Insert Table 6 here]

Since cryptocurrencies can be cross-listed on multiple exchanges, each with its own tick size, this natural heterogeneity in tick sizes for the same assets allows for a causal analysis of the 'migration effect' in a dual PLB market, as proposed by Werner et al. (2023). In this regression specification, assets with decreasing (or increasing) tick sizes are matched with identical assets listed on other exchanges where the tick size has remained unchanged, serving as the 'control group'. The matching process results are presented in Table 1. We select samples that match at least one control exchange leading to 182 treatment samples for tick size increases and 126 treatment samples for tick size decreases. Following previous analysis, we use a DiD approach to investigate the impact of decreasing (increasing) tick sizes on market quality. However, in this case, we also examine how tick-size decreases (increases) affect the market share of those assets on the treated exchanges. The regression specifications follow Equation 8. In addition to the market quality matrix as the dependent variables, we also include the market share of trades (denoted as *Trades share(%)*) and the market share of trading volume across exchanges (denoted as *Volume share(%)*). The control variables mirror those specified in Equation 8, except that the number of trades is omitted when *Trades share(%)* is the dependent variable to avoid potential multicollinearity.

Figure 6 illustrates the evolution of volume share and trades share of tick size increasing assets. These figures demonstrate that following a tick size increase, the share of volume and trades decreases for assets transitioning from an unconstrained spread to a constrained spread, as well as those remaining constrained, in the treatment exchanges. This suggests that increasing tick sizes sizes affects market share across various trading venues.

[Insert Figure 6 here]

We examine this in greater detail using a DiD regression framework, with results showns in Table 7. Panel A shows that contrary to theory, both unconstrained and constrained assets display an increase in spreads and reductions in volume and trade share. However, when we divide the unconstrained sample into those transitioning to either unconstrained or constrained in Panel B, we observe that 126 out of the 176 assets become constrained after the tick size increase. Consequently, most of the effect is limited to the 'Uncon2Cons' sample, for which predictions are difficult to make. In contrast, the coefficients in the 'Uncon2Uncon' group are not statistically significant. Moreover, splitting the sample by pre-leeway less than 2 post ticks shows that most of the effects are found in the constrained subsample and thus driven by mechanical and layering effects. In this sample, we see a clear increase in all measures of spread, increase in depth and loss in volume and trade share to other exchanges. The results suggest that, when tick sizes are increased, some traders of constrained assets migrate to other venues but there are insufficient incentives for traders of unconstrained assets to migrate to the treatment exchanges. These results are consistent with hypothesis 3 but do not align with hypothesis 4.

[Insert Table 7 here]

In Table 8, we examine the cross-exchange impact of tick size increases, with constraint level measured by the post tick size, following the analysis in Table 6. As previously, groups are classified using the 'A-B' transition, where A represents the constraint level based on the current tick, and B represents the constraint level based on the post-tick. The table confirms that splitting unconstrained assets from Panel A in Table 7 into those that become constrained and unconstrained using the post tick measure highlights the deterioration in market quality within the constrained sample. 'Uncon-Cons' sample has a significant increase in spreads, greater depth, lower volume and greater migration from the trading venue. In contrast, coefficients in the 'Uncon-uncon' assets do not generally see much significance. As expected, 'Cons-cons' assets generally see the largest increase in spread, depth, reduction on volume and the largest migration of trading from the treated venues across these three classifications.

[Insert Table 8 here]

Next, we explore how exchange dominance affects the market quality metrics and order flow after a tick size increase. We define the market fragmentation in the pre-period for the treated exchanges. Exchanges are categorized as 'Dominant' if their market share of trading volume in the specific asset exceeds the median value (44.86%) or 'Fragmented' if it is below. The results are shown in Table 9. For constrained assets experiencing a tick size increase, we observe that spread deterioration worsens as market dominance declines. The quoted spread for dominant markets increases by 1.57 bps, while it rises to 5.84 bps for fragmented markets. Other measures of spread follow the same pattern. Depth rises more in dominant markets, suggesting greater queuing, while volume does not decline as significantly as in fragmented marked. Short term volatility rises in both markets. The data also indicates that dominant exchanges do not experience a meaningful reduction in market share of either volume or trades, while the market share of volume and trades on fragmented exchanges declines by 6.14% and 9.09%, respectively. These results are intuitive, indicating that traders are more likely to migrate from fragmented rather than dominant exchanges when trading costs increase. This is in line with the finding of Foley et al. (2019), that trading on dominant exchanges is 'sticky'.

[Insert Table 9 here]

4.2.3 Tick size decrease

We now explore how reducing tick sizes impacts market quality, following the analysis from Section 4.2.2. Table 10 presents the results of the intensity DiD analysis for assets with decreased tick sizes, analogous to the analysis of tick increases shown in Table 5. When comparing the results between the constrained and unconstrained groups, we find that spread and depth changes are confined to the constrained group. This group exhibits statistically significant reductions of 14.87 bps in quoted spread, 7.44 bps in effective spread, and 4.70 (4.89) bps in realized 30 (60) second spread, mainly due to the mechanical effect. We observe a strong layering effect as the depth for constrained assets decreases and quotes become more dispersed across the finer pricing grid. We also notice a slight increase in volume, accompanied by a decrease in short-term volatility. The reduction in spreads and depth for constrained assets undergoing a tick size decrease is consistent with prior literature around decimalization (see, for example, Bacidore, 1997; Bessembinder, 2003; Chung et al., 2004). For the 'Uncon' group, the results are mixed and largely insignificant. Aside from volume, these results provide strong support for hypothesis 5 but do not support hypothesis 6. However, as has been shown previously, classifying assets solely on their level of constraint before the tick size decrease fails to capture the change in constraint levels and the terminal level of constraint after the tick size change.

[Insert Table 10 here]

To explore this setting, we divide constrained assets in Panel A based on the current tick size into 'Constrained to Constrained' and 'Constrained to Unconstrained' groups. These are reported in Panel B. In these two sub samples, we find stronger effects on the spread for assets that remain constrained after the tick size change, with a statistically and economically significant reductions of 73.13 bps in the quoted spread, 28.03 bps in the effective spread, and 13.63 bps in the realized 30 second spread. For the 'Constrained to Unconstrained' group, the spread narrows by a smaller magnitude, with reductions of 11.05 bps in the quoted spread and 6.27 bps in the effective spread. The 'Cons2Cons' group also exhibits a stronger reduction in depth as quotes disperse across more price points. These results provide a more robust analysis of the constrained group from Panel A. We find that assets with spreads that stay constrained after the tick size change benefit from additional mechanical reductions in tick size. This effect, combined with the layering effect, dominates, while binding spreads prevent undercutting. These results further strengthen our support for hypothesis 5. Conversely, for assets whose spreads become unconstrained after a tick size change, the beneficial mechanical and layering effects diminish, while the increased spread leeway allows for more detrimental undercutting. These assets show a more muted spread and depth response to a tick size decrease. More importantly, due to these opposing forces, there is no clear theoretical prediction, as the tick size in these assets may have already exceeded its optimal level. The outcome largely depends on the prevalence of undercutting, which depends on how unrestricted the spreads become following the tick size adjustment.

To address this issue, we also measure and report the post-tick size change spread leeway using the pre-tick size. By setting a 'Post leeway less than N pre ticks' threshold, we can classify assets as either 'relatively constrained' or 'relatively unconstrained'. This allows us to observe the layering effect in the 'relatively constrained' group and the undercutting effect in the 'relatively unconstrained' group. Based on the result of Figure 7, we choose the threshold of two, and use a threshold of three as a robustness test shown in Table A.8. In Panel C, we use this 'Post leeway less than 2 pre tick' measure to differentiate these 'relatively constrained' and 'relatively unconstrained' sub-samples. For the 'Cons2Uncon' assets with relatively constrained spread after the tick size decrease, we observe significantly improved spreads and decreasing depth, all influenced by the mechanical and layering effect. For the 'Cons2Uncon' assets with relatively unconstrained spread after the tick size decrease, we do not observe significant changes in spreads driven by undercutting.

[Insert Figure 7 here]

Although it would be useful to present results based both the current and post-tick constraint levels, as shown in Table 6 for assets with increasing tick sizes, there are no observations in the 'Cons-cons' group. This is because no exchange reduced its tick size to a level where spreads remained constrained after the tick size decrease. Consequently, these results are identical to Table 10 Panel A. The 'Uncon-Uncon' group results also align with the 'Uncon' group in Panel A as a decrease in tick size for a spread-unconstrained asset will, by construction, result in a more unconstrained asset after the tick size change. This supports the earlier findings that the mechanical and layering channel dominate undercutting.

Given the insignificant results on volume, we now turn our attention to the role of other exchanges where these assets are traded, examining how traders' ability to migrate across exchanges impacts market quality. Figure 8 graphically shows that tick size decreasing exchanges capture some market share from competing venues, particularity when the spreads are binding.

[Insert Figure 8 here]

The corresponding regression results of the influence of a tick size decrease on migration of trades and volume across the exchanges is displayed in Table 11. For the 'Unconstrained' group, we do not observe any significant results between spreads, depth and migration effect. However, for the 'Constrained' group, we see narrowing of spreads and reduced depth. Moreover, we also observe migration to the trading venue, which might explain why volume, contrary to theoretical expectations of a decline in the within-exchange model, is not significantly different from zero. For the 'Cons2Cons' group, we observe a strong mechanical and layering effect, characterized by narrowing spreads and decreasing depth. Compared to the 'Cons2Uncon' group, the migration effect is stronger, capturing a 17.59% increase in volume share and a 20.14% increase in trade share from other venues. We observe an improved spread when the post-leeway is less than two pre-tick sizes for the 'Cons2Uncon' group. For the 'Cons2Uncon' assets with a post-leeway of more than two pre-ticks, we observe the realized spread within 30 seconds increases by 3.70 bps, while the depth decreases. This suggests that undercutting is more prevalent in this group following the tick size reduction. These results support our hypothesis 7 but there is not sufficient evidence in support of hypothesis 8. As previously stated, we are unable to further breakdown Panel A into current and post-tick constraint levels because we not have any observations in the 'Constrained to constrained' group.

[Insert Table 11 here]

For robustness, we also examine whether market fragmentation influences our results. Werner et al. (2023) empirically test their predictions on tick size reductions in the Japanese and US markets and find contrasting results. They attribute these differences to the distinct market structures, noting that the Japanese market is much less fragmented than the US market. Following their analysis, we conduct a DiD regression for tick size decreasing assets based on the underlying market fragmentation. We categorize the treated exchanges into 'Dominant' where the trading volume larger than the median value (15.91%), and 'Fragmented', where the trading volume is below the median value. We focus on 'Constrained to constrained' assets, where we have a clear theoretical prediction on the effect. The results are as shown in Table 12. It indicates that for the Cons2Cons group, dominant exchanges have much more pronounced decreases in spreads, greater volume and capture significantly more order flow compared to fragmented exchanges. Dominant exchanges see a 26.78% increase in trade share and a 22.82% increase in volume share, while fragmented exchanges see a 13.58% increase in trade share and a 12.46% increase in volume share.

[Insert Table 12 here]

5 Conclusion

Tick sizes are a crucial design feature for exchanges. Recent theoretical literature models the impact of tick size changes on market quality through four different transmission channels: undercutting, layering, mechanical, and migration. Although empirical studies indicate that the optimal tick size must balance the prevention of excessive undercutting and queuing, data limitations have hindered the validation of the models. We address this gap by leveraging our unique cryptocurrency setting, analyzing 420 tick size increases and 434 tick size decreases to comprehensively test all predictions of these theoretical models simultaneously.

Our analysis indicates that spread-constrained assets exhibit the most significant changes in market quality. These assets see the largest increases in spread and depth when tick sizes are raised, and the greatest decreases when tick sizes are reduced. Spread-constrained assets also experience the greatest order flow migration, with tick size increases leading to migration away from, and tick size decreases leading to migration towards, the trading venue. These symmetric results suggest that within exchanges, the mechanical and layering channels are predominant, whereas the migration channel is highly significant across different exchanges. Although we confirm that undercutting harms liquidity provision, we do not observe significant changes in market quality for unconstrained assets, indicating that this transmission channel is significantly weaker than the others.

We further show that for spread-constrained assets, dominant exchanges experience a larger decrease in spreads, a smaller decrease in depth, and greater inflow when tick sizes are reduced. Conversely, fragmented exchanges exhibit larger widening in spreads, smaller increases in depth, and greater outflow when tick sizes are increased. These results show that beneficial tick size changes are more pronounced on dominant exchanges, while detrimental changes are more evident on fragmented exchanges.

Overall, our analysis of almost 1,000 tick size changes across multiple exchanges reveals that tick sizes can be neither too big to constrain spreads, nor too small, to encourage undercutting - they need to be set 'just right': a challenge that global regulators and exchanges are still struggling to optimize.

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6 Tables

Table 1 – Sample Selection
This table presents the final sample. Panel A lists the number of assets affected by the tick size changes as announced by the exchanges, along with the final sample used in our analysis. The full selection process is detailed in Appendix B. Panel B displays the cross-exchange matching of assets affected by tick size change with those that remain unaffected.

Panel A: Final sample of events with tick size changes

Event day	Event exchange	Tick size change		No tick size	Tick size change (Final sample)	
		Increase	Decrease	change	Increase	Decrease
2021/3/18	OKX Spot	9	23	508	3	6
2021/8/2	OKX Spot	2	81	417	1	76
2021/8/26	Binance Spot	331	107	848	284	84
2022/6/1	OKX Spot	20	41	577	15	41
2022/7/28	OKX Spot	85	17	539	81	15
2023/1/18	KuCoin Spot	1	222	1110	0	190
2023/3/2	Binance US	44	52	243	36	22
	Total	492	543		420	434

Panel B: Cross-exchange matching of assets with tick size changes

Tick size increase	Matching exchanges (#)	0	1	2	3	4	5
	Matching assets (#)	238	89	60	25	5	3
Tick size decrease	Matching exchanges (#)	0	1	2	3	4	5
	Matching assets (#)	308	82	22	15	3	4

Table 2 – Undercutting Runs and Liquidity Provision Before and After the Tick Size Change
This table presents the variables averaged across increasing and decreasing tick sizes, three weeks before and after the tick size change. Panel A shows undercutting metrics including: the *Total number of undercuts*; the mean *Number of runs* in each 15-minute window with at least two undercuts; proportion of *One tick undercuts* in every run; the mean *Step size* of each undercut per run, in USD or post tick size; the mean *Run duration* in seconds; the mean *Price difference* between the beginning and the end of the run, in bps or post ticks; and the mean number of *Seconds between trades* between trades. Panel B presents liquidity provision variables, measured at 15-minute intervals including: the *Average order exposure* of the best bid or ask exposure; the average number of price steps a market order consumes (*Average price step*); and the mean number of *Resting limit orders* at the same price step. Standard errors are displayed in parentheses. The 'Diff' column reports the difference in means before and after the tick size change. All differences are statistically significant at the 1% levels, based on a two-tailed t-test.

	Assets with increasing tick sizes			Assets with decreasing tick sizes		
	Pre	Post	Diff	Pre	Post	Diff
Panel A: Undercutting runs and undercutting profitability						
Undercutting run groups(#)	159,297,325	36,747,375		7,799,961	69,207,290	
Number of runs (#)	198.97	51.11	-147.87	22.17	94.74	72.57
	(361.94)	(135.39)		(83.30)	(252.44)	
One tick undercuts(%)	63.43	74.90	11.47	90.36	65.02	-25.33
	(36.33)	(33.31)		(20.54)	(33.18)	
Step size(post tick)	0.28	1.34	1.06	10.95	3.18	-7.77
	(0.48)	(0.93)		(1.84)	(3.28)	
Step size($)	0.004	0.009	0.005	0.003	0.001	-0.002
	(0.01)	(0.02)		(0.01)	(0.01)	
Run duration(s)	2.49	4.02	1.52	5.05	3.02	-2.03
	(6.38)	(9.36)		(11.92)	(8.67)	
Price difference(post_tick)	0.99	3.13	2.14	21.16	9.65	-11.52
	(1.95)	(4.16)		(16.46)	(13.25)	
Price difference(bps)	4.41	7.74	3.33	16.53	7.68	-8.84
	(6.52)	(9.06)		(16.84)	(10.59)	
Seconds between trades(s)	73.04	78.73	5.69	240.81	180.64	-60.17
	(229.04)	(238.15)		(433.20)	(363.10)	
Panel B: Liquidity provision						
Average order exposure (s)	14.32	40.13	25.81	178.89	79.72	-99.18
	(63.54)	(127.06)		(288.49)	(186.95)	
Average price step (#)	1.21	1.11	-0.10	1.13	1.31	0.18
	(0.26)	(0.17)		(0.34)	(0.58)	
Resting limit orders (#)	1.74	2.79	1.04	2.78	1.61	-1.17
	(1.16)	(1.94)		(2.27)	(1.13)	

Table 3 – Market Quality Before and After the Tick Size Change
This table reports market quality metrics for all assets with changing tick sizes, measured at 15-minute intervals. The variables are averaged across increasing and decreasing tick sizes, three weeks before and after the tick size change. *Quoted spread* is time-weighted and measured in bps. *Effective spread* is volume-weighted, measured in bps. *Realized spread* is volume-weighted at 30 and 60 seconds, measured in bps. *Depth* is the time-weighted $1,000 volume quoted at the best prices. *Volume* is the total trading volume in $100,000. *Short-term volatility* is based on midpoint-to-midpoint returns and measured in bps. *Volatility* is the currency-time high-low price range scaled by the high-low midpoint in percent. *Trades* is the number of trades. *Volume share* and *Trades share* represent the proportion of total volume and trades, respectively, occurring in the sample exchanges. Standard errors are reported beneath the mean values. The 'Diff' column reports the difference in means before and after the tick size change. All differences are statistically significant at the 1% levels, based on a two-tailed t-test.

	Assets with increasing tick sizes			Assets with decreasing tick sizes		
	Pre	Post	Diff	Pre	Post	Diff
Quoted Spread (bps)	22.04	20.93	-1.11	75.60	58.58	-17.02
	(24.81)	(22.56)		(102.32)	(66.49)	
Effective Spread (bps)	19.67	19.04	-0.63	66.18	58.55	-7.63
	(22.86)	(26.02)		(95.51)	(213.03)	
Realized Spread (30s, bps)	7.14	5.71	-1.43	32.34	27.44	-4.90
	(20.82)	(22.67)		(76.90)	(206.79)	
Realized Spread (60s, bps)	7.00	5.79	-1.21	32.23	27.18	-5.05
	(22.09)	(23.52)		(79.08)	(207.74)	
Depth ($1,000)	4.31	12.73	8.43	3.31	1.08	-2.23
	(21.21)	(86.69)		(12.43)	(3.32)	
Volume ($100,000)	2.11	2.30	0.19	0.16	0.28	0.12
	(9.73)	(9.54)		(0.82)	(1.77)	
Short-term volatility (bps)	2.91	3.64	0.73	11.49	9.65	-1.84
	(2.38)	(3.38)		(14.81)	(12.94)	
Volatility (%)	0.82	0.82	-0.01	0.86	0.91	0.05
	(0.66)	(0.70)		(1.00)	(0.96)	
Trades (100#)	2.77	2.62	-0.15	0.40	0.58	0.18
	(8.20)	(7.66)		(0.84)	(1.24)	

Table 4 – Undercutting Runs and Liquidity Provision
This table presents the impact of undercutting runs on liquidity provision, separately for the full sample and for assets with either increasing or decreasing tick sizes. For brevity, only the coefficient of the number of runs (in thousands) on various liquidity provision metrics measured in 15-minute intervals is reported. *Number of runs* and *Trades* are measured in thousands. *LnDepth* and *LnVolume* are the logarithms of *Depth* and the dollar *Volume*, respectively. The number of observations for *Resting limit orders* is generally lower than for other liquidity provision metrics. We estimate the number of resting limit orders for market orders that span multiples price steps, excluding the last price level for each market order. This exclusion results in fewer observations. Robust standard errors, controlling for event-asset and time, are reported in parentheses. All regression models control for event and asset fixed effects. All dependent variables are winsorized at the 99th percentile. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

	Full sample	Tick size decrease	Tick size increase
Average order exposure	-31.00***	-43.51***	-24.73***
	(2.56)	(6.31)	(2.44)
Average price step	0.14***	0.13***	0.16***
	(0.02)	(0.03)	(0.03)
Resting limit orders	-1.56***	-0.76***	-1.98***
	(0.19)	(0.12)	(0.29)
LnDepth	-1.16***	-0.72***	-1.40***
	(0.10)	(0.10)	(0.14)
LnVolume	0.04	0.42***	-0.20***
	(0.07)	(0.10)	(0.07)
Short term volatility	-2.11***	-3.50***	-0.85***
	(0.29)	(0.69)	(0.21)
Observations	2,477,705	1,009,333	1,468,372
FE		Event-Asset	

Table 5 – Within-Exchange DiD Analysis of Tick Size Increases by Current Tick Constraint Level

This table presents the coefficients of the interaction term $Treat \times Post$ in a DiD analysis of tick size increase intensity within exchanges, where the constraint level is based on the current tick. The treated group includes assets with increased tick sizes in treatment exchanges, while the control group comprises matching assets within same exchange. In Panel A, columns 'Uncon' and 'Cons' represent treated assets with unconstrained and constrained spreads in the pre-period, respectively, with constraint levels determined by the quoted spread at the current tick. Assets are categorized as 'Cons' if the ratio exceeds the 80% cutoff and 'Uncon' if it is at or below 80%. In Panel B, 'Uncon2Cons' shows the treated assets with unconstrained spreads before the tick size increase that become constrained after the event, while 'Uncon2Uncon' shows the treated assets that remain unconstrained in the post-period. Panel C, further divides the 'Uncon2Cons' assets from Panel B into 'True' and 'False' groups based on whether the pre-leeway of an asset is less than two post ticks. All dependent variables are winsorized to the 95th percentile for each asset. Robust standard errors, controlling for event-asset and date, are reported in parentheses. The number of observations for effective and realized spreads is an upper bound, as they cannot be calculated without trades within a 15-minute interval. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regressions control for event and asset fixed effects.

	Panel A: Constraint level based on current tick		Panel B: Constraint changing based on current tick		Panel C: Pre-leeway less than 2 post ticks	
	Uncon	Cons	Uncon2Cons	Uncon2Uncon	True	False
Quoted	-0.58	5.40***	0.8	-2.72**	2.63***	-1.02
Spread	(0.54)	(1.47)	(0.54)	(1.05)	(0.79)	(0.65)
Effective	0.15	6.02**	1.32***	-1.91**	2.55***	0.09
Spread	(0.43)	(2.27)	(0.44)	(0.87)	(0.56)	(0.61)
Realized	-0.77**	3.39**	-0.16	-1.89**	0.59	-0.94**
Spread (30s)	(0.35)	(1.50)	(0.29)	(0.75)	(0.39)	(0.38)
Realized	-0.61*	3.59**	-0.14	-1.48*	0.62	-0.93**
Spread (60s)	(0.35)	(1.43)	(0.29)	(0.76)	(0.39)	(0.38)
LnDepth	0.72***	1.90***	0.98***	0.29***	1.33***	0.63***
	(0.04)	(0.22)	(0.05)	(0.04)	(0.08)	(0.05)
LnVolume	0.03	-0.41	-0.04	0.14*	-0.08***	-0.01
	(0.04)	(0.29)	(0.03)	(0.07)	(0.03)	(0.05)
Short term	0.76***	0.36	0.80***	0.70***	0.78***	0.82***
volatility	(0.10)	(0.22)	(0.11)	(0.19)	(0.16)	(0.14)
Obs.	3,401,336	66,048	2,080,512	1,320,824	1,040,256	1,040,256
Treat	412	8	252	160	126	126
Control	412	8	252	160	126	126
FE			Event-Asset			

Table 6 – Within-Exchange DiD Analysis of Tick Size Increases by Post Tick Constraint Level This table presents the coefficients of the interaction term $Treat \times Post$ for tick size increase intensity in a DiD analysis within exchanges. The control group comprises assets with no tick size changes, matched to the tick size increasing assets based on the same tick size and similar daily trades. The results for groups categorized by constrained level based on current tick and post tick. Column (1) signifies assets that remain unconstrained under both the current-tick and post-tick rules. Column (2) refers to assets that are unconstrained under the current-tick rule but constrained under the post-tick rule. Column (3) presents assets that remain constrained under both the current-tick and post-tick rules, same as the 'Cons' group in Panel A of Table 5. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, controlling for exchange-asset and date, are reported in parentheses. The number of observations for effective and realized spreads is an upper bound, as they cannot be calculated without trades within a 15-minute interval. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regression models control for exchange and asset fixed effects.

	(1)	(2)	(3)
Constraint based on current tick	Uncon	Uncon	Cons
Constraint based on post tick	Uncon	Cons	Cons
Quoted	-3.85***	1.44***	5.40***
Spread	(1.04)	(0.54)	(1.47)
Effective	-2.44***	1.61***	6.02**
Spread	(0.86)	(0.44)	(2.27)
Realized	-2.22***	0.03	3.39**
Spread (30s)	(0.75)	(0.29)	(1.50)
Realized	-1.81**	0.05	3.59**
Spread (60s)	(0.76)	(0.28)	(1.43)
LnDepth	0.26***	1.00***	1.90***
	(0.04)	(0.05)	(0.22)
LnVolume	0.13*	-0.04	-0.41
	(0.07)	(0.03)	(0.29)
Short term	0.59***	0.86***	0.36
volatility	(0.16)	(0.13)	(0.22)
Obs.	1,296,056	2,105,280	66,048
Treat	157	255	8
Control	157	255	8
FE		Event-Asset	

Table 7 – Cross-Exchange DiD Analysis of Tick Size Increases by Current Tick Constraint Level

This table presents the coefficients of the interaction term $Treat \times Post$ for tick size increase intensity in a DiD analysis across exchanges, where the constrained level is based on the current tick. The treated group consists of assets with increased tick sizes in treatment exchanges, while the control group comprises the same assets in control exchanges. In Panel A, subsamples 'Uncons' and 'Cons' refer to treated assets with unconstrained and constrained spreads in the pre-period, respectively, with constrained levels determined by the quoted spread in the current tick. Assets are categorized as 'Cons' if the ratio exceeds the 80% cutoff and 'Uncon' if it is at or below 80%. In Panel B, subsamples of 'Uncon2Cons' are the treated assets with unconstrained spread before the tick size increase but with constrained spread after the event. Subsamples of 'Uncon2Uncon' are the treated assets with unconstrained spread in the pre and post period. In Panel C, the 'Unconstrained to Constrained' assets from Panel B are divided into 'True' and 'False' groups based on whether the pre-leeway of an asset is less than 2 post tick. The robust test for thresholds of 3 post tick is shown in Table A.9. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, controlling for exchange-asset and date, are reported in parentheses. The number of observations for effective and realized spreads is an upper bound, as they cannot be calculated without trades within a 15-minute interval. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regression models control for exchange and asset fixed effects.

	Panel A: Constrained level based on current tick.		Panel B: Constrained changing level based on current tick.		Panel C: Pre-leeway less than 2 post tick	
	Uncon	Cons	Uncon2Cons	Uncon2Uncon	True	False
Quoted	3.43***	4.03***	4.11***	0.19	5.39***	0.62
Spread	(0.84)	(0.71)	(1.03)	(1.28)	(1.35)	(0.86)
Effective	1.92***	3.19***	2.24***	0.42	3.08***	0.34
Spread	(0.66)	(0.62)	(0.82)	(0.82)	(1.15)	(0.74)
Realized	1.50***	1.79***	1.66**	0.24	2.23***	0.11
Spread (30s)	(0.52)	(0.37)	(0.64)	(0.81)	(0.81)	(0.79)
Realized	1.46***	1.96***	1.60**	0.25	2.13***	0.16
Spread (60s)	(0.51)	(0.47)	(0.62)	(0.85)	(0.79)	(0.80)
LnDepth	0.51***	1.63***	0.66***	0.2	0.92***	0.36***
	(0.10)	(0.24)	(0.11)	(0.20)	(0.13)	(0.11)
LnVolume	-0.25**	-0.35***	-0.26**	0.05	-0.22	-0.19**
	(0.12)	(0.12)	(0.13)	(0.13)	(0.15)	(0.09)
Short term	0.58***	0.35**	0.70***	0.24**	0.73***	0.64***
volatility	(0.12)	(0.15)	(0.17)	(0.12)	(0.24)	(0.13)
Volume	-3.58***	-2.87	-4.77***	-1.26	-5.44***	-2.52***
share	(0.88)	(2.23)	(0.96)	(1.23)	(1.14)	(0.87)
Trades	-2.94***	-13.55**	-4.64***	-0.64	-7.70***	-3.27***
share	(0.99)	(5.53)	(1.13)	(1.20)	(1.18)	(0.94)
Obs.	1,975,079	86,688	1,419,468	555,611	891,926	527,542
Treat	176	6	126	50	79	47
Control	304	15	219	85	138	81
FE	Exchange-Asset					

Table 8 – Cross-Exchange DiD Analysis of Tick Size Increases by Post Tick Constraint Level
This table shows the coefficients of the interaction term $Treat \times Post$ for tick size increase intensity in a DiD analysis across exchanges. The treated group is the tick size increasing assets in treatment exchanges, while the control group is the same assets in control exchanges. The results for groups categorized by constrained level based on current tick and post tick. Column (1) shows assets that remain unconstrained under both the current-tick and post-tick rules. Column (2) refers to assets that are unconstrained under the current-tick rule but constrained under the post-tick rule. Column (3) presents the assets that remain constrained under both the current-tick and post-tick rules, same as the 'Cons' group in Panel A of Table 7. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, controlling for exchange-asset and date, are reported in parentheses. The number of observations for effective and realized spreads is an upper bound, as they cannot be calculated without trades within a 15-minute interval. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regression models control for exchange and asset fixed effects.

	(1)	(2)	(3)
Constraint based on current tick	Uncon	Uncon	Cons
Constraint based on post tick	Uncon	Cons	Cons
Quoted	-0.11	4.49***	4.03***
Spread	(1.26)	(1.07)	(0.71)
Effective	-0.1	2.49***	3.19***
Spread	(0.82)	(0.83)	(0.62)
Realized	0.26	1.80***	1.79***
Spread(30s)	(0.82)	(0.64)	(0.37)
LnDepth	0.14	0.68***	1.63***
	(0.19)	(0.10)	(0.24)
LnVolume	0.05	-0.34**	-0.35***
	(0.13)	(0.15)	(0.12)
Volume	-2.91	-4.51***	-2.87
share	(2.03)	(0.96)	(2.23)
Trades	-3.29**	-3.71***	-13.55**
share	(1.58)	(1.16)	(5.53)
Obs.	551,508	1,423,571	86,688
Treat	49	127	6
Control	85	219	15
FE		Exchange-Asset	

Table 9 – Cross-Exchange DiD Analysis of Tick Size Increases by Post Tick Constraint Level and Market Fragmentation

This table presents the coefficients of the interaction term $Treat \times Post$ for tick size increase intensity in a DiD analysis, categorized by market fragmentation across exchanges. The treated group consists of tick size increasing assets in treatment exchanges, while the control group comprises the same assets in control exchanges. Subsample 'Cons2Cons' refer to treated assets with constrained spreads before and after the tick size increases as measured by the quoted spread in the post tick. Assets are categorized as 'Cons' if the ratio exceeds the 80% cutoff. Market fragmentation is defined in the pre-period for the treated exchanges. Exchanges are categorized as 'Dominant' if their trading volume share exceeds the median value (44.86%) and 'Fragmented' if it is 44.86% or below. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, controlling for exchange-asset and date, are reported in parentheses. The number of observations for effective and realized spreads is an upper bound, as they cannot be calculated without trades within a 15-minute interval. The number of observations vary slightly across dependent variables. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regression models control for exchange and asset fixed effects.

	Cons2Cons	
	Dominant	Fragmented
Quoted	1.57***	5.84***
Spread	(0.35)	(1.49)
Effective	1.07***	4.06**
Spread	(0.28)	(1.56)
Realized	0.60**	2.52*
Spread (30s)	(0.26)	(1.44)
Realized	0.65**	2.31
Spread (60s)	(0.26)	(1.40)
LnDepth	0.95***	0.93***
	(0.11)	(0.10)
LnVolume	-0.09	-0.38***
	(0.07)	(0.12)
Short term	0.22***	1.17***
volatility	(0.05)	(0.27)
Volume	0.64	-6.14***
share	(1.39)	(0.95)
Trades	-2.54	-9.09***
share	(1.93)	(1.44)
Obs.	694,639	733,112
Treat	68	57
Control	101	121
FE	Exchange-Asset	

Table 10 – Within-Exchange DiD Analysis of Tick Size Decreases by Current Tick Constraint Level

This table presents the coefficients of the interaction term $Treat \times Post$ in a DiD analysis of tick size decrease intensity within exchanges, where the constraint level is based on the current tick. The treated group includes assets with decreased tick sizes in treatment exchanges, while the control group comprises matching assets within same exchange. In Panel A, columns 'Uncon' and 'Cons' refer to treated assets with unconstrained and constrained spreads in the pre-period, respectively, with constrained levels measured by the quoted spread in the current tick. Assets are categorized as 'Cons' if the ratio exceeds the 80% cutoff and 'Uncon' if it is at or below 80%. In Panel B, 'Cons2Cons' shows the treated assets with constrained spread before the tick size decrease period that remain constrained in the post-period, while 'Cons2Uncon' shows the treated assets that became unconstrained after the tck size decrease. Panels C further divides the 'Cons2Uncon' assets from Panel B into 'True' and 'False' groups based on whether the post pre-leeway of an asset is less than two pre ticks. All dependent variables are winsorized to the 95th percentile for each asset. Robust standard errors, controlling for event-asset and date, are reported in parentheses. The number of observations for effective and realized spreads is an upper bound, as they cannot be calculated without trades within a 15-minute interval. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regressions control for event and asset fixed effects.

	Panel A: Constraint level based on current tick		Panel B: Constraint changing level based on current tick		Panel C: Post leeway less than 2 pre ticks	
	Uncon	Cons	Cons2Cons	Cons2Uncon	True	False
Quoted	-7.32	-14.87***	-73.13***	-11.05***	-24.30***	3.47
Spread	(9.00)	(2.74)	(17.27)	(2.51)	(3.98)	(2.50)
Effective	1.24	-7.44***	-28.03***	-6.27***	-12.91***	-0.35
Spread	(2.67)	(2.17)	(8.02)	(2.25)	(4.12)	(1.70)
Realized	1.51	-4.70**	-13.63**	-4.13**	-10.23***	1.32
Spread(30s)	(2.35)	(1.94)	(5.20)	(2.05)	(3.92)	(1.28)
Realized	1.31	-4.89**	-14.04**	-4.32**	-10.35***	1.06
Spread(60s)	(2.35)	(1.94)	(5.30)	(2.05)	(3.90)	(1.33)
LnDepth	-0.15	-0.83***	-1.83***	-0.76***	-1.03***	-0.46***
	(0.10)	(0.06)	(0.15)	(0.06)	(0.09)	(0.07)
LnVolume	0.12	0.11**	0.69**	0.08	0.09	0.05
	(0.10)	(0.06)	(0.27)	(0.06)	(0.08)	(0.07)
Short term	-2.56***	-1.43***	-0.47	-1.50***	-1.07**	-1.96***
volatility	(0.56)	(0.31)	(1.35)	(0.32)	(0.46)	(0.37)
Obs.	825,308	2,757,192	173,240	2,583,952	1,353,984	1,229,968
Treat	100	334	21	313	164	149
Control	100	334	21	313	164	149
FE			Event-Asset			

Table 11 – Cross-Exchange DiD Analysis of Tick Size Decreases by Current Tick Constraint Level

This table presents the coefficients of the interaction term $Treat \times Post$ for tick size decrease intensity in a DiD analysis across exchanges. The treated group consists of assets with decreased tick sizes in treatment exchanges, while the control group comprises the same assets in control exchanges. In Panel A, subsamples 'Uncon' and 'Cons' refer to treated assets with unconstrained and constrained spreads in the pre-period, respectively, with constrained levels determined by the quoted spread in the current tick. Assets are categorized as 'Cons' if the ratio exceeds the 80% cutoff and 'Uncon' if it is at or below 80%. In Panel B, subsamples of 'Cons2Cons' are the treated assets with constrained spread in the pre and post period. Subsamples of 'Cons2Uncon' are the treated assets with constrained spread before the tick size decrease but with unconstrained spread after the event. Panels C shows the 'Cons2Uncon' group with the measure 'post leeway less than two pre tick', which is the quoted spread after the event, measured in pre tick. In Panel C, the 'Constrained to Unconstrained' assets from Panel B are divided into 'True' and 'False' groups based on whether the post-leeway of an asset is less than two in pre tick. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, controlling for exchange-asset and date, are reported in parentheses. Observations are based on using trades share as the dependent variable. The number of observations for effective and realized spreads is an upper bound, as they cannot be calculated without trades within a 15-minute interval. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regression models control for exchange and asset fixed effects.

	Panel A: Constraint level based on current tick		Panel B: Constraint changing level based on current tick		Panel C: Post leeway less than 2 pre ticks	
	Uncon	Cons	Cons2Cons	Cons2Uncon	True	False
Quoted	-5.08	-8.03**	-53.77***	-2.36	-13.88***	1.79
Spread	(6.33)	(3.51)	(16.88)	(2.60)	(3.98)	(1.68)
Effective	-1.73	-3.35*	-23.50***	-1.32	-8.25***	0.97
Spread	(6.19)	(1.79)	(4.47)	(1.76)	(3.12)	(1.46)
Realized	2.2	0.28	-6.78***	1.01	-4.53*	3.70**
Spread(30s)	(4.28)	(1.36)	(2.43)	(1.46)	(2.51)	(1.86)
Realized	1.86	0.15	-6.67***	0.85	-4.47*	3.52*
Spread(60s)	(4.23)	(1.33)	(2.33)	(1.42)	(2.43)	(1.84)
LnDepth	-0.23	-0.94***	-1.95***	-0.82***	-1.03***	-0.57***
	(0.26)	(0.09)	(0.19)	(0.09)	(0.13)	(0.10)
LnVolume	0.6	-0.01	0.93***	-0.13	0.24	0.11
	(0.47)	(0.18)	(0.28)	(0.20)	(0.21)	(0.12)
Short term	-0.19	-0.53**	-0.46	-0.55**	-1.07***	-0.71*
volatility	(1.70)	(0.24)	(0.51)	(0.26)	(0.34)	(0.41)
Volume	-0.95	4.45***	17.59***	2.77**	4.99***	0.26
share	(3.71)	(1.17)	(4.16)	(1.16)	(1.73)	(1.60)
Trades	0.34	4.69***	20.14***	2.73**	4.86***	-2.4
share	(4.14)	(1.16)	(3.69)	(1.17)	(1.16)	(1.83)
Obs.	212,853	1,135,035	139,746	995,289	539,182	456,107
Treat	24	101	12	89	42	46
Control	28	175	22	153	87	59
FE			Exchange-Asset			

Table 12 – Cross-Exchange DiD Analysis of Tick Size Decreases by Current Tick Constraint Level and Market Fragmentation

This table presents the coefficients of the interaction term $Treat \times Post$ for tick size decrease intensity in a DiD analysis across exchanges based on the market fragmentation. The treated group is the tick size decreasing assets in treatment exchanges, while the control group is the same assets in control exchanges. Assets are categorized as 'Cons' if the pre tick ratio exceeds the 80% cutoff. We also define the market fragmentation in the pre-period for the treated exchanges. Exchanges are categorized as 'Dominant' if their trading volume share exceeds the median value (15.91%) and 'Fragmented' if it is 15.91% or below. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, controlling for exchange-asset and date, are reported in parentheses. Observations are based on using trades share as the dependent variable. The number of observations for effective and realized spreads is an upper bound, as they cannot be calculated without trades within a 15-minute interval. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regression models control for exchange and asset fixed effects.

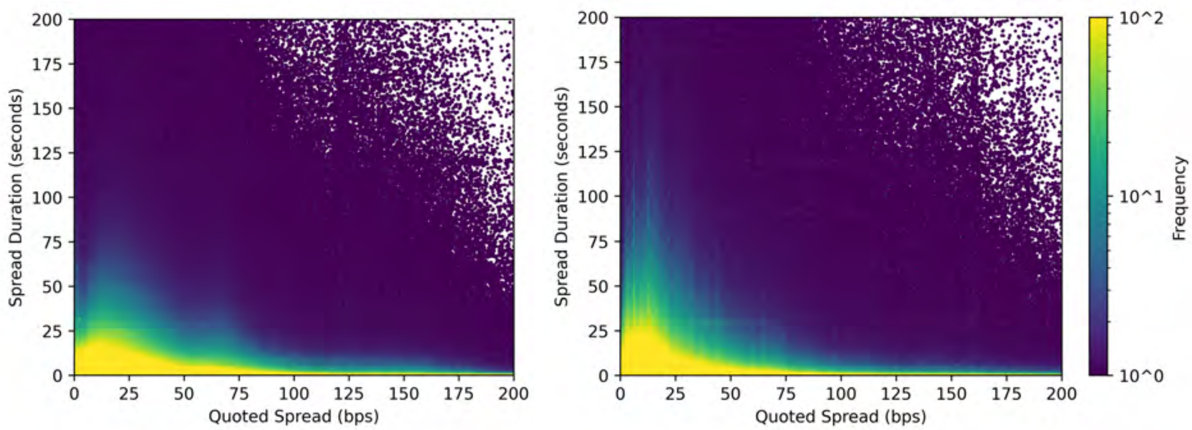
	Cons2Cons	
	Dominant	Fragmented
Quoted	-89.55***	-7.9
Spread	(21.94)	(7.22)
Effective	-33.09***	-14.96***
Spread	(7.24)	(4.56)
Realized	-14.10***	-1.06
Spread (30s)	(2.82)	(2.89)
Realized	-13.95***	-1.17
Spread (60s)	(2.49)	(3.00)
LnDepth	-1.81***	-2.06***
	(0.26)	(0.21)
LnVolume	1.04**	0.79**
	(0.43)	(0.30)
Short term	-1.20**	0.02
volatility	(0.55)	(0.69)
Volume	22.82***	12.46***
share	(6.93)	(3.77)
Trades	26.78***	13.58***
share	(5.91)	(3.15)
Obs.	65,930	73,816
Treat	7	5
Control	9	13
FE	Exchange-Asset	

7 Figures

Figure 1 – Spread Duration with Frequency Distribution before and after the Tick Size Change
This figure illustrates the heatmap showing the relationships between the relative quoted spread (in bps) and the spread duration (in seconds) for assets with increasing (Panel A) and decreasing (Panel B) tick sizes. The color map indicates the frequency at each point on a logarithmic scale. The axes are truncated at 200 seconds and 200 bps.

Panel A: Tick Size Increase

(a) Before **(b) After**



Panel B: Tick Size Decrease

(a) Before **(b) After**

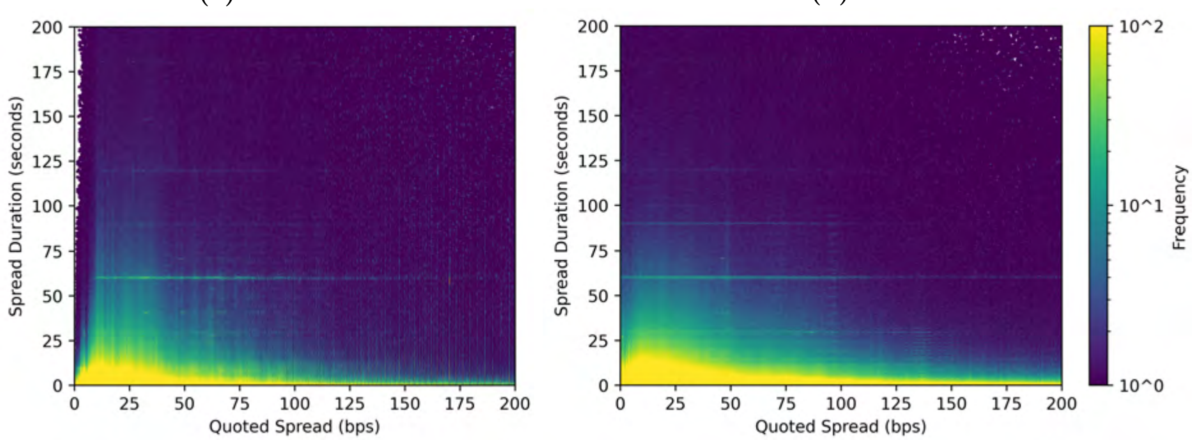


Figure 2 – Comparison of Relative Tick Size and Relative Quoted Spread for Assets with Changing Tick Sizes

Panels A and B display the truncated time-weighted quoted spread against the relative tick size for assets with increasing and decreasing tick sizes, respectively. The relative tick is estimated by scaling the tick size by the price, expressed in bps. In each panel, the horizontal axis represents the relative tick size in bps (a logarithmic scale is shown in Figure A.3), and the vertical axis shows the time-weighted quoted spread in bps. The values for each treated asset are averaged across pre- and post-periods. The dots represent treated assets in the pre-period, while crosses indicate treated assets in the post-period. The dashed line, 'y=x', signifies a binding spread.

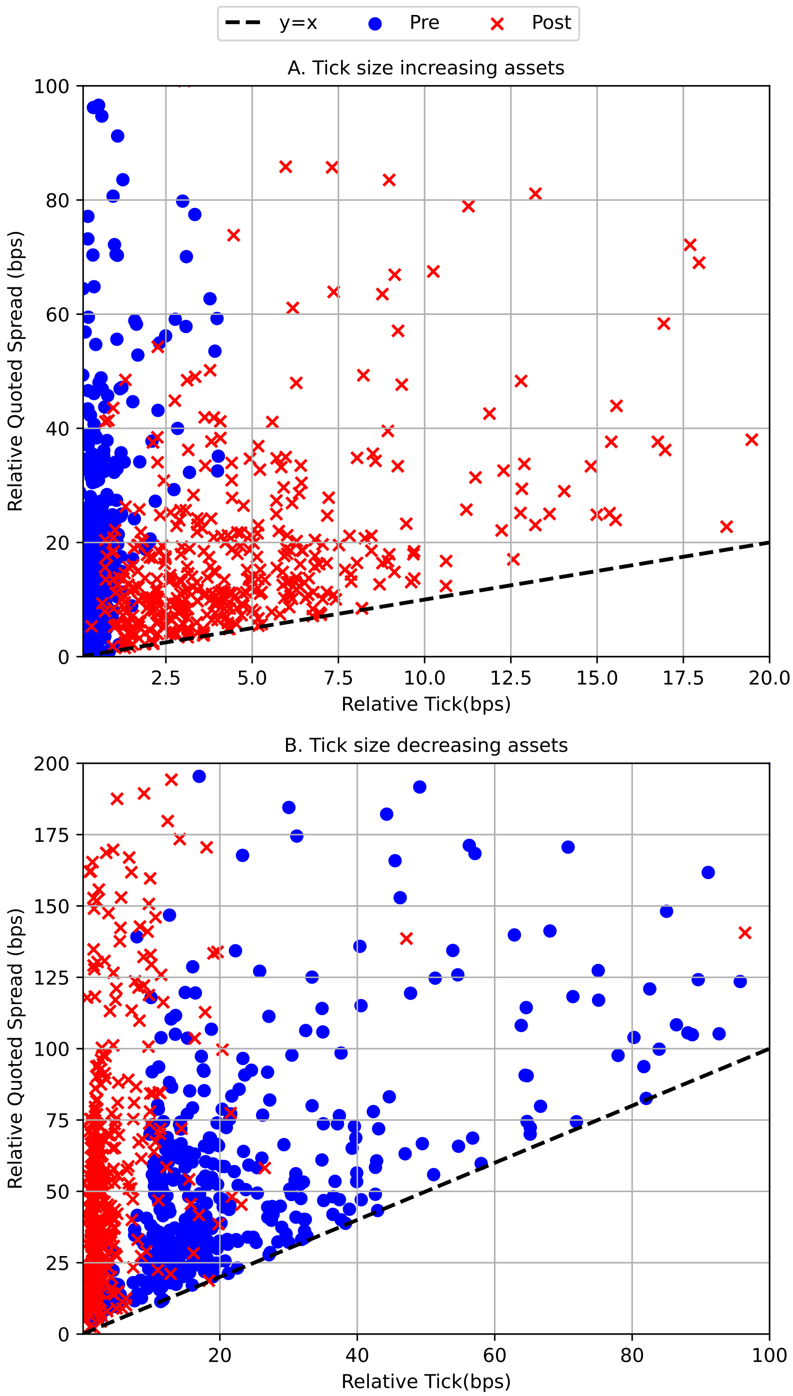


Figure 3 – Histogram for the constrained ratio of pooling assets in pre-period.
This figure depicts the histogram for the constrained ratio of the pooling assets during the pre-period. The pooling assets set contains samples categorized as: a) increasing treatment assets in treatment exchange, b) increasing control assets in treatment exchange, c) increasing treatment assets in control exchange, d) increasing control assets in control exchanges, e) decreasing treatment assets in treatment exchange, f) decreasing control assets in treatment exchange, g) decreasing control assets in control exchanges, h) decreasing treatment assets in control exchange. The vertical dashed line marks the 80% cutoff ratio. Assets are categorized as 'Constrained' if the ratio exceeds 80%, and 'Unconstrained' if the ratio is at or below the cutoff.

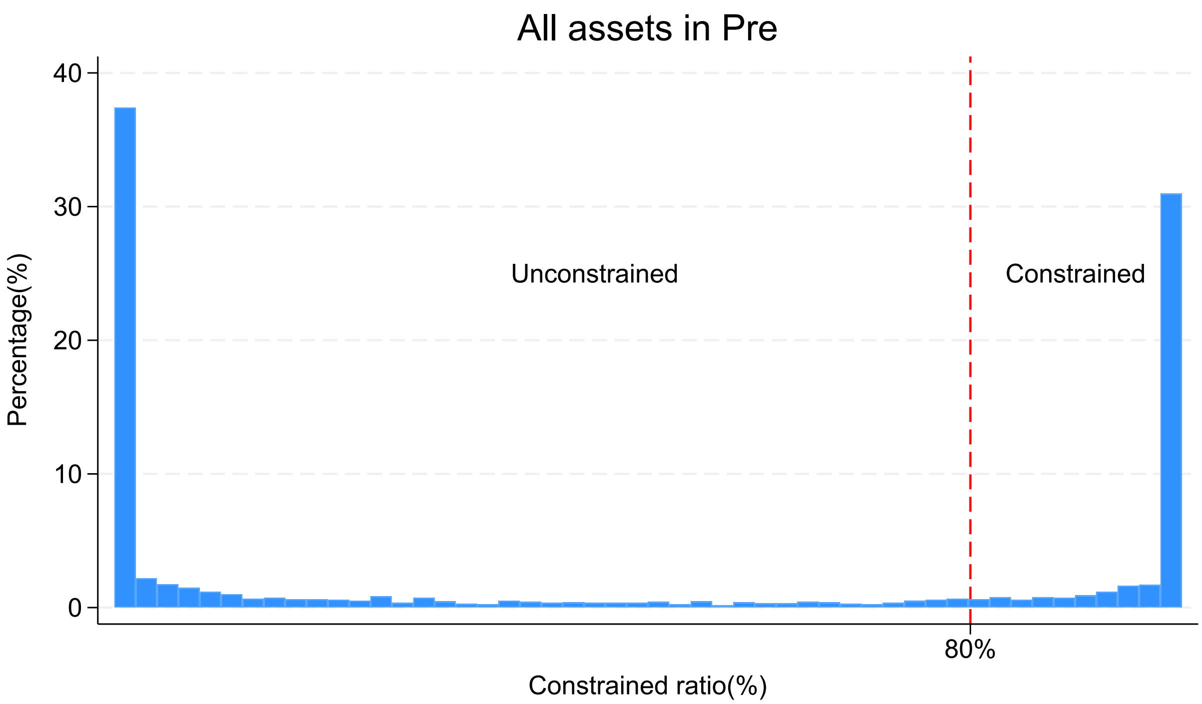
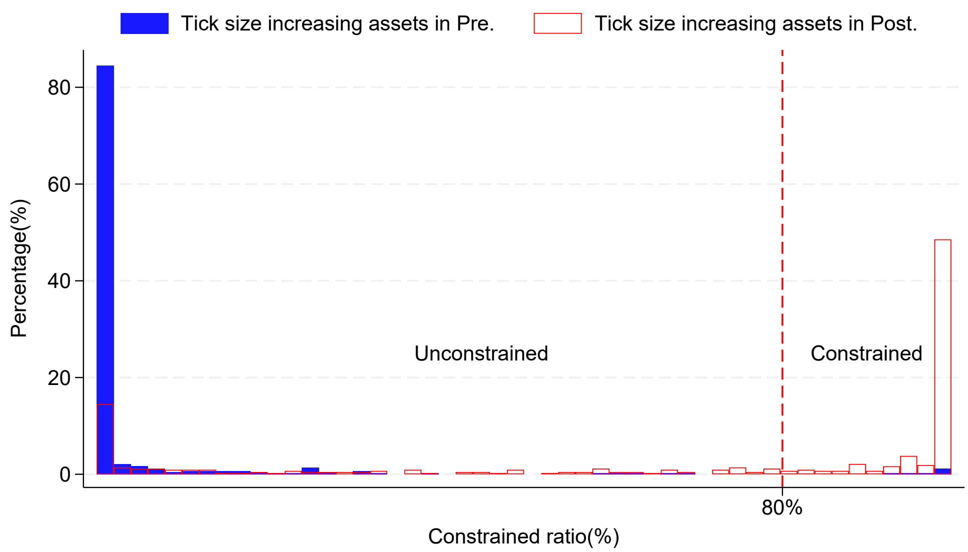


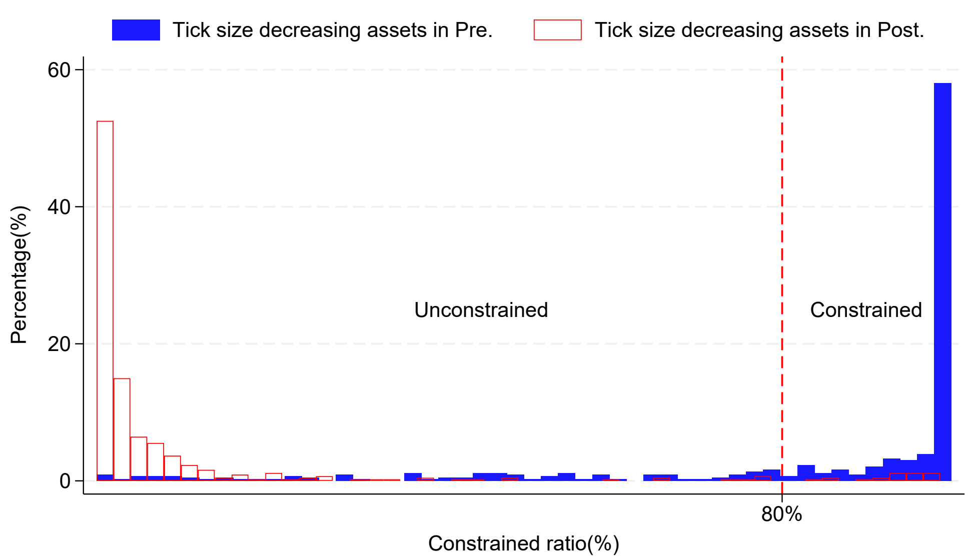
Figure 4 – Histogram of the constrained ratio for assets with changing tick sizes during the pre- and post-periods.
This figure plots the histogram of the constrained ratio for assets with increasing (or decreasing) tick sizes during the pre- and post-periods. The cutoffs and classification rules for 'Constrained' and 'Unconstrained' are consistent with those outlined in Figure 3. The table below each figure shows the proportion of each group relative to the total tick size changing assets during the pre- and post-periods.

Panel A: Tick size increase



Cutoff	Classification in the pre-period	Percent(%)	Classification in the post-period	Percent(%)
80%	Unconstrained	98.10	Unconstrained	38.10
	Constrained	1.90	Constrained	61.90

Panel B: Tick size decrease

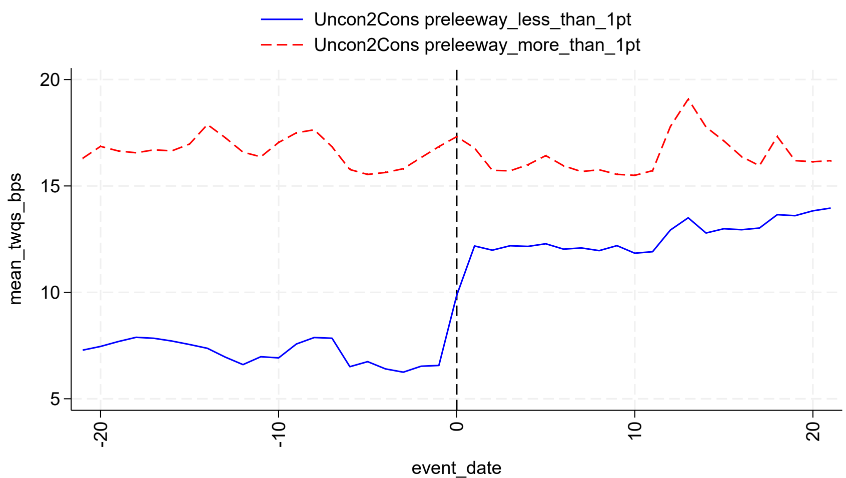


Cutoff	Classification in the pre-period	Percent(%)	Classification in the post-period	Percent(%)
80%	Unconstrained	23.04	Unconstrained	95.16
	Constrained	76.96	Constrained	4.84

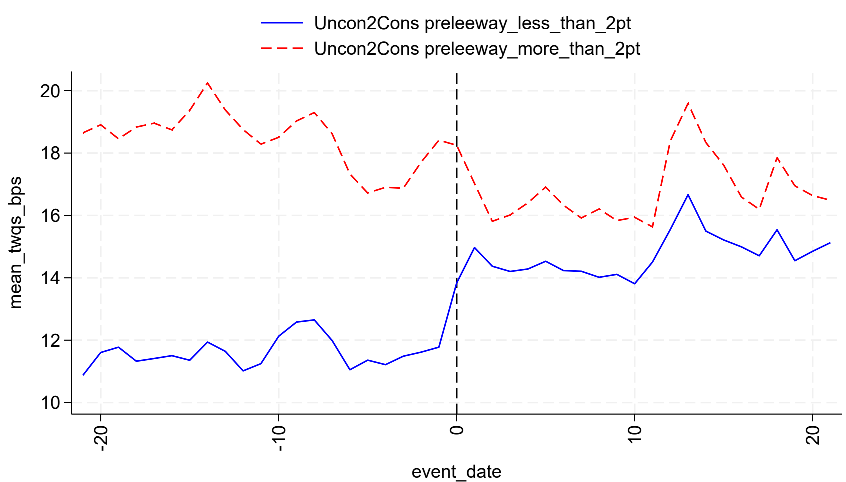
Figure 5 – The average quoted spread for unconstrained versus constrained assets within exchanges, categorized by pre-leeway measured in post-tick increments

This figure depicts the average quoted spread for 'Unconstrained to Constrained' asset, where the unconstrained level is based on the current tick. The data is categorized by pre-leeway, measured in post tick (denoted as 'pt' in figures). The horizontal axis, labeled event_date, indicates the event date, with the tick size change day marked as 0. The vertical axis shows the mean quoted spread in bps, averaged daily within each group. The solid line represents assets with limited pre-leeway before the tick size increase, while the dashed line represents assets with sufficient pre-leeway.

Panel A: Pre-leeway threshold of one post tick



Panel B: Pre-leeway threshold of two post ticks



Panel C: Pre-leeway threshold of thee post ticks

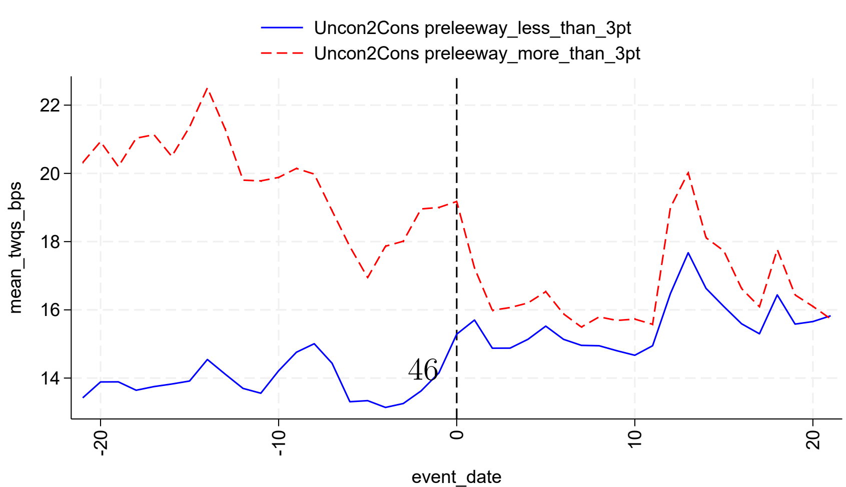
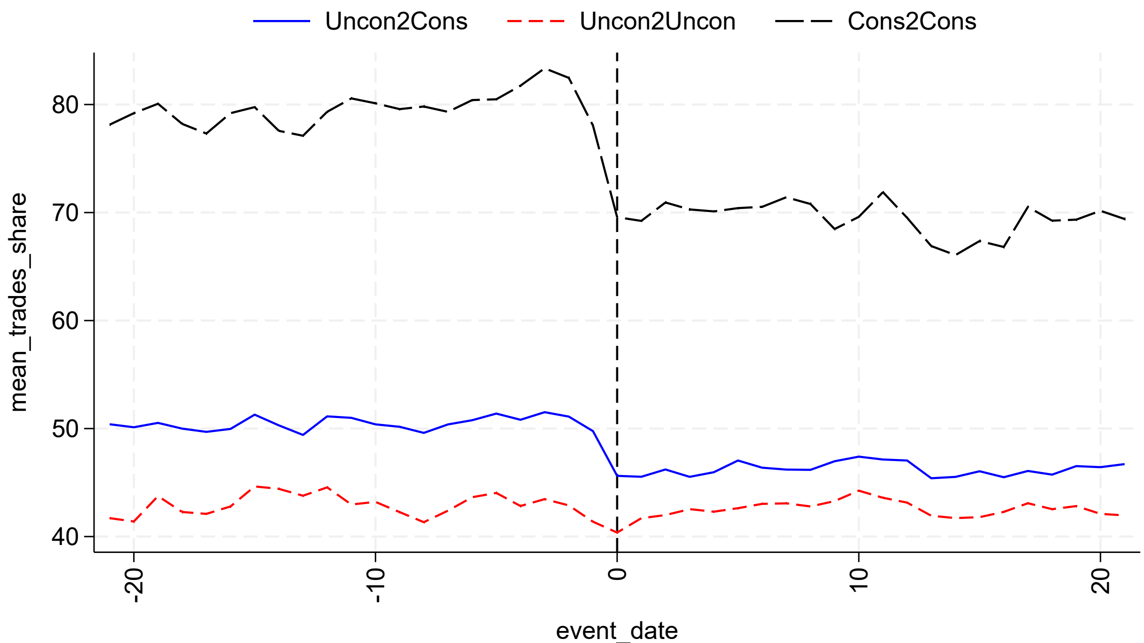


Figure 6 – The evolution of market share of trade and volume for assets with increased tick size, categorized by changes in constraint status

This figure illustrates the evolution of both the trades share and volume share during the sample period for assets experiencing an increase in tick size. Panel A depicts the changes in trades share for three subgroups: assets transitioning from unconstrained to constrained tick sizes (Uncon2Cons), assets remaining unconstrained (Uncon2Uncon), and assets remaining constrained (Cons2Cons), both before and after the relevant events. Panel B displays the corresponding changes in volume share for these subgroups. The horizontal axis indicates the event date, with the tick size change day marked as 0. The vertical axis represents the daily average market share of trades (volume) across all assets, as a percentage.

Panel A: Market share of trades



Panel B: Market share of volume

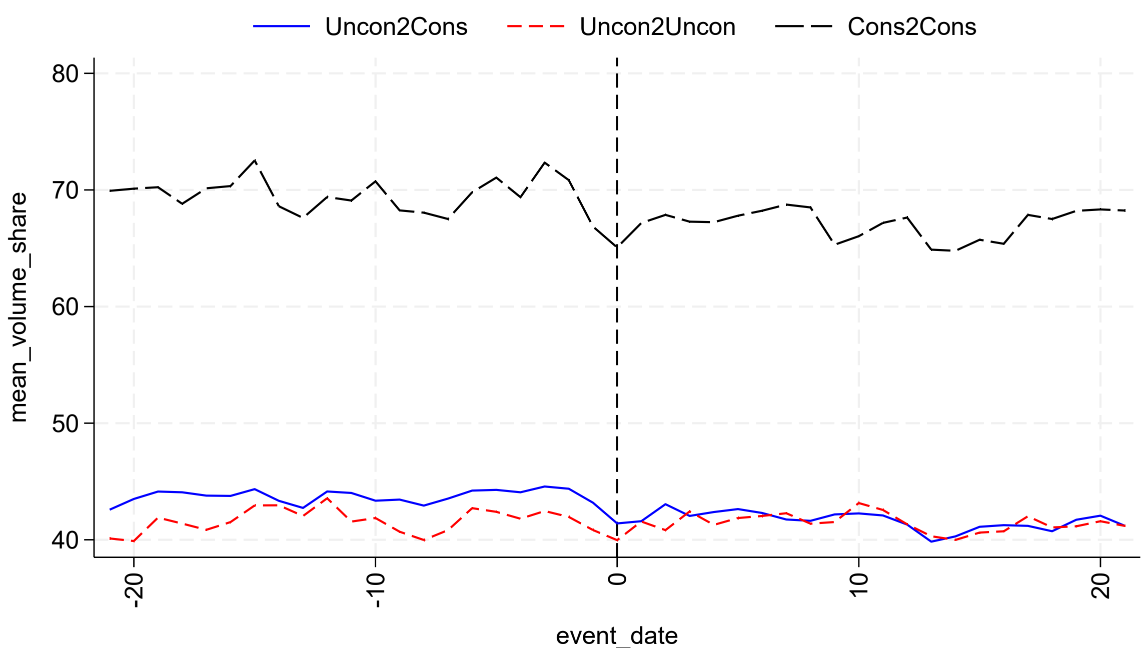
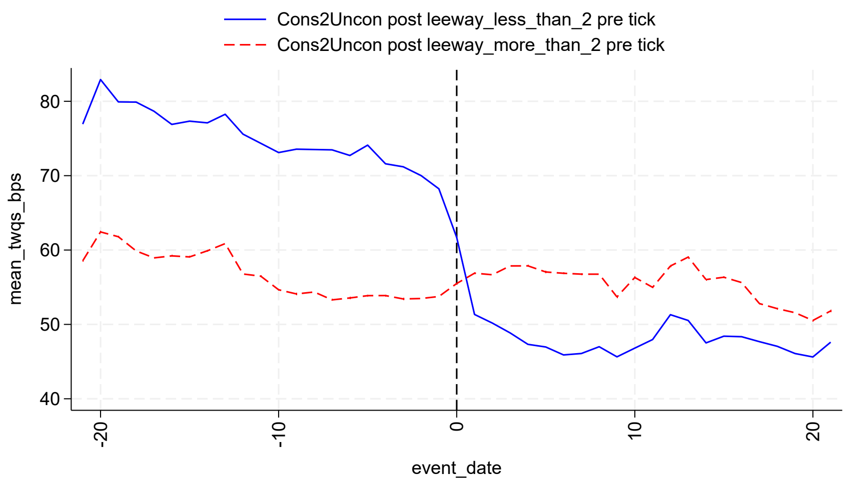


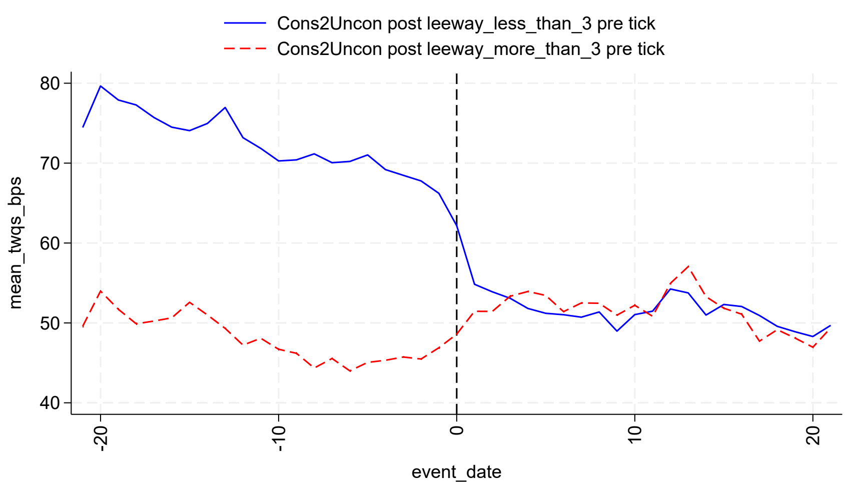
Figure 7 – The average of quoted spread for constrained to unconstrained assets within exchanges, categorized by the post-leeway measured in pre-tick

This figure illustrates the average quoted spread for 'Constrained to Unconstrained' assets, where the unconstrained level is based on the current tick. The data is categorized by post-leeway, measured in pre-tick increments. The horizontal axis indicates the event date, with the tick size change day marked as 0. The vertical axis shows the mean quoted spread in bps, averaged daily within each group. The solid line represents assets with limited post-leeway after the tick size decrease, while the dashed line represents assets with sufficient post-leeway.

Panel A: Post-leeway threshold set at two pre ticks



Panel B: Post-leeway threshold set at three pre ticks



Panel C: Post-leeway threshold set at five pre ticks

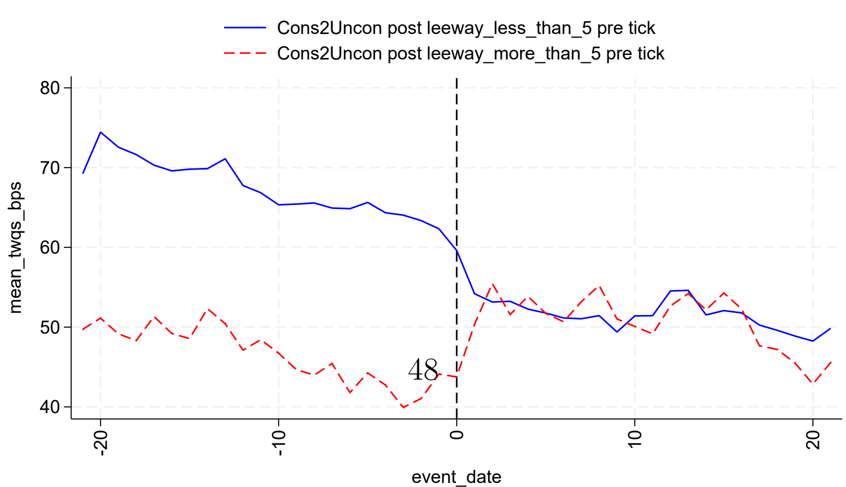
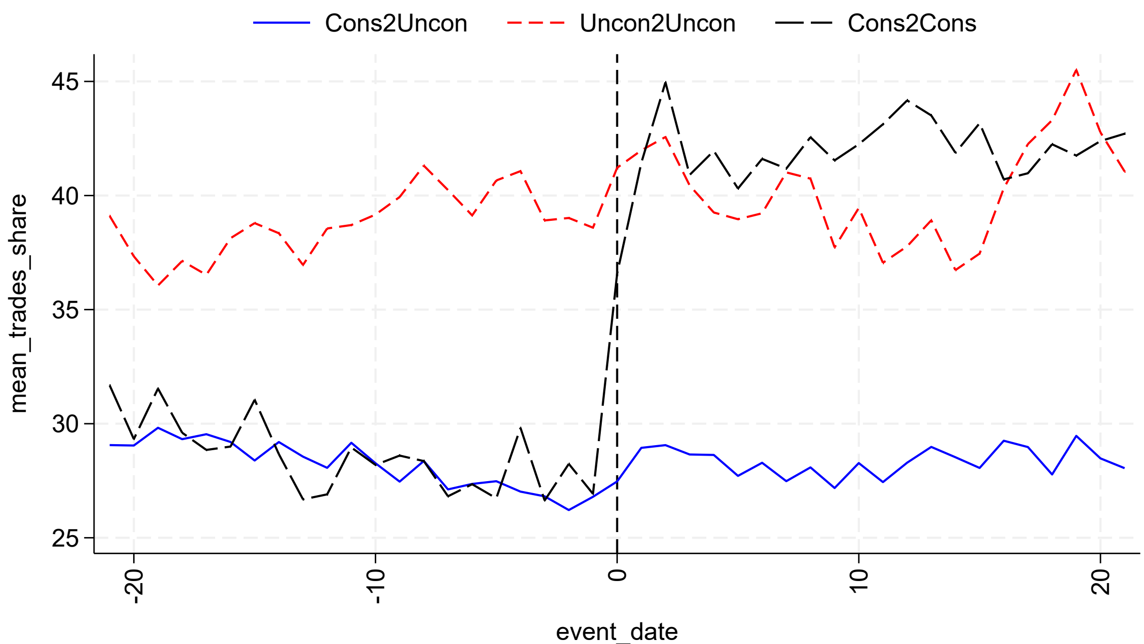


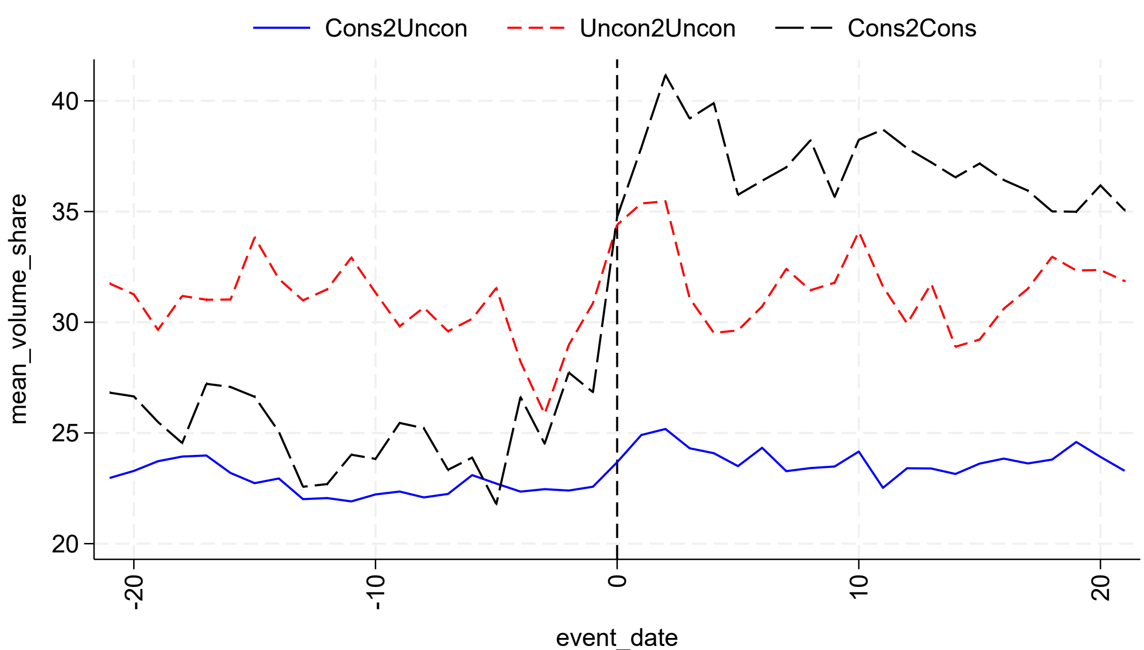
Figure 8 – The evolution of market share of trades and volume for assets with decreased tick size, categorized by changes in constraint status

This figure illustrates the evolution of both the trades share and volume share during the sample period for assets experiencing an decrease in tick size. Panel A depicts the changes in trades share for three subgroups: assets transitioning from constrained to unconstrained tick sizes (Con2Unons), assets remaining unconstrained (Uncon2Uncon), and assets remaining constrained (Cons2Cons), both before and after the relevant events. Panel B displays the corresponding changes in volume share for these subgroups. The vertical axis represents the daily average market share of trades (volume) across all assets, as a percentage.

Panel A: Market share of trades



Panel B: Market share of volume



Appendices

A Precision and Speed of Matching Engines

This section evaluates the precision and speed of the matching engines utilized by the cryptocurrency exchanges in our sample, based on Foley et al. (2023a). Table A.1 presents the timestamp precision and the matching engine speed. Figure A.1 shows the proportional change of the Empirical Cumulative Distribution Function of sample assets on Kraken. Figure A.2 illustrates the distribution of millisecond remainders across exchanges.

Table A.1 – The precision and speed of matching engines across sample events and control exchanges

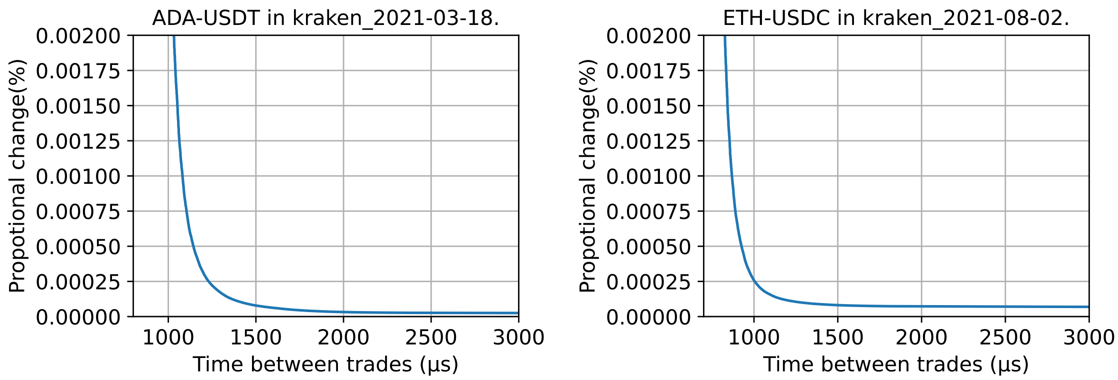
Event	Sample Assets	Precision	The Ratio of Identical Timestamp	Matching Engine Speed
binance_2021-08-26	BTCTUSD	ms	39.38%.	Fast
binance-us_2023-03-02	BTCUSDT	ms	29.27%	Fast
kucoin_2023-01-18	BTC-USDT	ms	41.01%	Fast
okex_2022-06-01	BTC-USDT	ms	53.15%	Fast
okex_2022-07-28	BTC-USDT	ms	55.62%	Fast
okex_2021_08-02	BTC-USDT	ms	41.60%	Fast
okex_2021-03-18	BTC-USDT	ms	43.82%	Fast
coinbase_2021-08-26	BTC-USDT	μs	19.38%	Fast
kraken_2021-08-26	ETH-USDT	μs	0%	Slow

Note: This table shows the timestamp precision and matching engine speed of the sample exchanges during the three weeks before and after the event. Exchanges with fast matching engines can match multiple limit orders to a single market order with the same timestamp. We calculate the ratio of identical timestamps in the total trade records. If this ratio exceeds 20% then we classify the matching engine as 'Fast'.

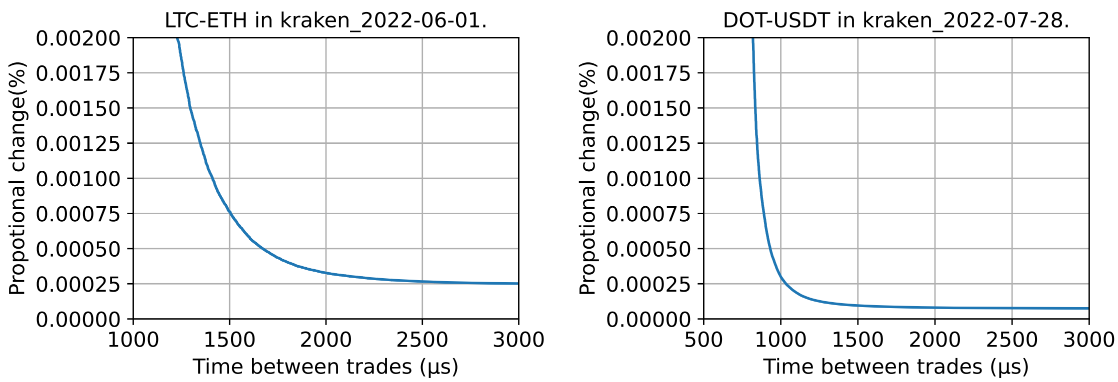
Executed limit orders are provided by Tardis. However, the aggregation of these orders depends on the precision and speed of exchanges' matching engines. A fast and precise matching engine can accurately identify the same market order by matching the trade side and timestamp. Conversely, a slow matching engine with imprecise timestamps may label the same market order with different timestamps, distorting the actual trade data and introducing bias in the construction of market quality metrics. We follow Foley et al. (2023a) and examine the precision and matching engine speed of sample exchanges. The results in Table A.1 show that all sample exchanges, except Kraken, have fast matching engines. For these exchanges, we match multiple limit orders with the same timestamp and side to a single market order. For Kraken, we aggregate the executed limit orders to 'recover' market orders based on a time window. To determine the appropriate time window, we plot the proportional change in time between trades, as shown in Figure A.1.

Figure A.1 – The proportional change for a sample assets on Kraken from 2021 to 2023
Panels A, B and C plot sample assets traded on Kraken in 2021, 2022 and 2023, respectively. The horizontal axis represents the time between trades in microseconds, while the vertical axis shows the proportional change in percentage. The proportional change is calculated as the first difference in the Empirical Cumulative Distribution Function (ECDF) relative to the cumulative ECDF.

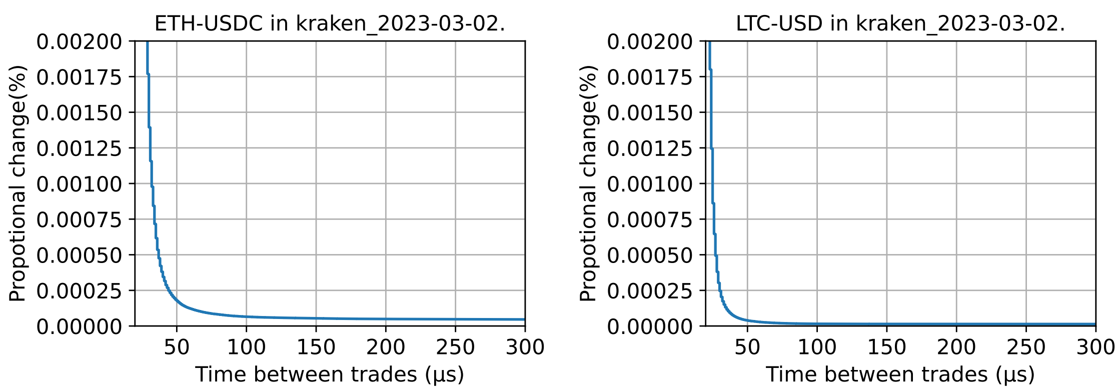
Panel A: 2021



Panel B: 2022



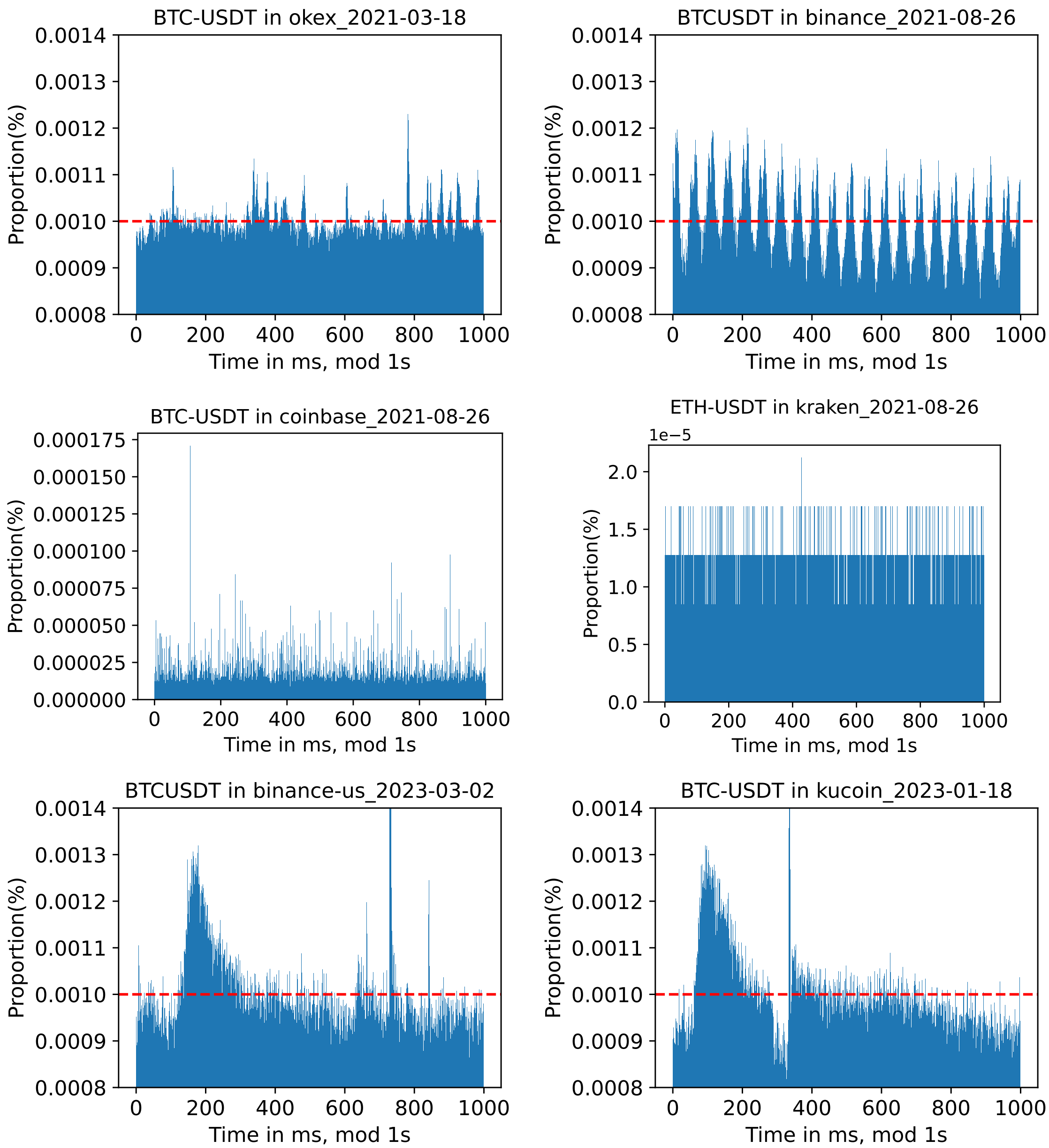
Panel C: 2023



The plots in Figure A.1 shows that Kraken's matching engine update in 2023 has altered the threshold for steady-state increase in the ECDFs across the three years. For the sample assets in 2021 and 2022, the proportional change stabilizes after 2 millisecond. In 2023, the proportional change converges within 200 microseconds. Therefore, we choose 2ms time window for 2021 and 2022, and 200μs time window for 2023 to aggregate Kraken's trade data.

To identify imprecise exchanges, we plot the millisecond remainder buckets for the samples and examine whether the trades are equally distributed across each bucket from 0 to 999. As shown in Figure A.2, all exchanges have approximately 1/1000th of trades in each millisecond remainder bucket, indicating that all the sample exchanges are precise.

Figure A.2 – The distribution of millisecond remainders for sample exchanges
This figure shows the distribution of millisecond remainders for six sample exchanges. The horizontal axis represents the 1000 buckets within 1 second, with each bucket corresponding to a millisecond remainder. The vertical axis shows the proportion of remainders in the entire dataset. The dashed line marks the 1/1000 proportion.



B Sample Selection

This appendix presents the details of the sample selection process. Table A.2 lists the tick-size changing assets excluded due to inconsistencies with the collected announcements.

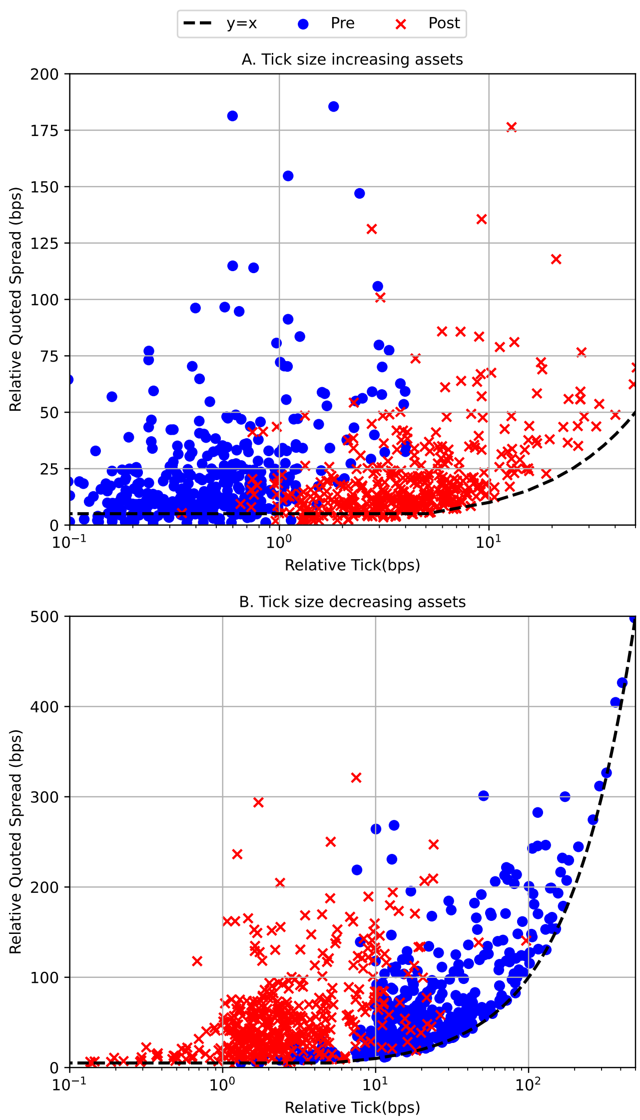
Table A.2 – The tick-size changing assets which are inconsistent with the announcement
This table lists the assets for which the tick-size estimation based on quotes data is inconsistent with the announcement. 'Changed but not announced' indicates that the currency pair is not listed in the announcement, but our estimation shows daily tick size changes during the sample period. 'Announced in other events' refers to cases where the tick size change for an asset pair is attributed to other tick-size change events. 'Not changed but announced' means the asset pair is listed in the tick-size change announcement but does not change based on our tick-size estimation.

Event	Reason for Inconsistency	asset pairs
binance_2021-08-26	Changed but not announced	1INCHDOWNUSDT , AAVEDOWNUSDT, ADADOWNUSDT, DOTDOWNUSDT, FILDOWNUSDT, LINKDOWNUSDT, SXPDOWNUSDT
	Announced in other events	LTCDOWNUSDT, TRXDOWNUSDT, UNIDOWNUSDT, XLMDOWNUSDT, XTZDOWNUSDT
binance-us_2023-03-02	Not changed but announced	ACHUSD, ENJUSD
	Changed but not announced	MATICBUSD
kucoin_2023-01-18	Announced in other events	AAVE3S-USDT, ACQ-USDC, APE3S-USDT, CARE-USDT, GALAX3S-USDT, GMT3S-USDT, LTC3S-USDT, SOL3S-USDT, SWFTC-USDC, SWFTC-USDT, XWG-USDT
	Not changed but announced	EPK-USDT, OPCT-ETH, PSL-USDT
okex_2021-03-18	Announced in other events	1INCH-USDT, EOS-USDT, KNC-USDT, NEO-USDT, SUN-USDT, TORN-USDT, XRP-USDT, XTZ-USDT
okex_2021-08-02	Not changed but announced	ZYRO-USDT
okex_2022-06-01	Announced in other events	LUNA-USDT
okex_2022-07-28	Not changed but announced	MXC-USDT

C Logarithmic Relative Tick Size vs. Relative Quoted Spread for Tick Size Changing Assets

This section provides a detailed analysis of time-weighted quoted spread in relation to the relative tick. Figure A.3 shows the comparison of relative tick size in logarithmic and relative quoted spread for tick size increasing and decreasing assets.

Figure A.3 – Comparison of Relative Tick Size and Relative Quoted Spread
Panels A and B present the time weighted quoted spread vs the relative tick size for assets with increasing and decreasing tick sizes. Panel A truncates x at 50 and y at 200. Panel B truncates x at 50 and y at 500. The relative tick is estimated by the tick size to the price, in bps. The horizontal axes represent the relative tick in bps, displayed on a logarithmic scale. Vertical axes show the time weighted quoted spread in bps. The value of each treated asset is the average across pre or post period. Dots represent the treated assets in the pre-period, while crosses depict the treated assets in the post period. The dashed 'y=x' line provide the reference of constrained relationship between relative tick and quoted spread.



D The samples in Cons2Uncon and Uncon2Cons from Panel C, Table 6

This section illustrates the samples for Cons2Uncon and Uncon2Cons in Panel C, Table 6, and in Panel C, Table 8. Figure A.4 illustrates the quoted spread (in bps, current tick and post tick) change before and after the tick size increase. Table A.3 and A.4 present the summary for quoted spread (in bps and current tick) in the pre and post period.

Figure A.4 – Comparison of Quoted Spread for Cons2Uncon assets from Panel C, Table 6. This figure presents the evolution of quoted spread (in bps, current tick and post tick) before and after the tick size increase for 'Cons2Uncon' assets from Panel C, Table 6. These assets are all categorized as 'Uncon2Uncon' under the current tick constraint rule. For these 19 'Cons2Uncon' assets, the average of quoted spread in bps is represented by the solid blue line, the quoted spread in current tick by the green long-dash line, and the quoted spread in post tick by the red dash line. The figure indicates that, for these 19 assets, the quoted spread increases. The quoted spread in current tick drops from around 50 pre-tick to 5 post-tick. The quoted spread in post tick increase from about 3 post-tick to 6 post-tick, resulting in the constraint level changing from constrained to unconstrained.

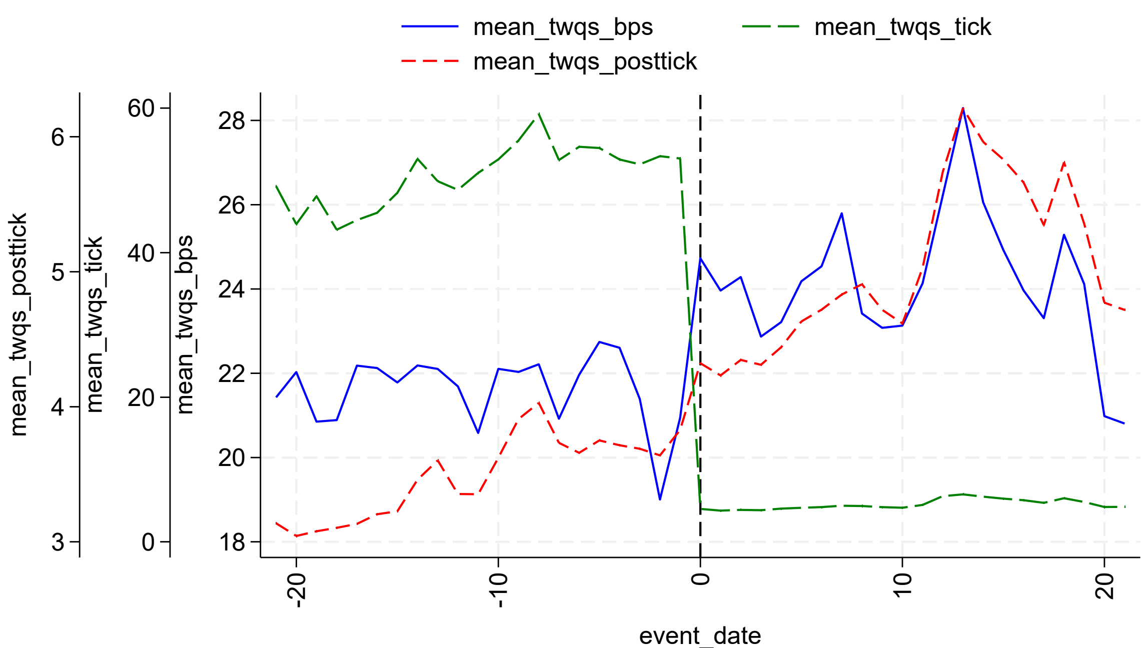


Table A.3 – Summary for Cons2Uncon and Uncon2Cons samples in Panel C, Table 6.
This table presents the average quoted spread (in bps and current tick) for assets in the Cons2Uncon and Uncon2Cons groups from Panel C, Table 6. The post-tick constraint level is based on the post-tick, while the current tick constraint level refers to the pre-period tick (pre-tick) and post-period tick (post-tick). Notably, all Cons2Uncon assets under the post-tick constraint rule are identified as Uncon2Uncon under the current tick rule. The quoted spread is averaged across pre- and post-periods for each asset pair. Tick size dp refers to the decimal places for tick size, such as 0.01 for 2 dp.

				Pre			Post		
Post tick constraint level	Current tick constraint level	Event id	Asset id	Quoted spread (bps)	Quoted spread (pre tick)	Tick size dp	Quoted spread (bps)	Quoted spread (post tick)	Tick size dp
Cons	Uncon	1	44	18.40	33.88	3	10.21	5.44	2
2	2	1	190	9.61	27.26	4	9.89	5.13	3
Uncon	Uncon	1	214	22.02	36.20	4	20.61	4.95	3
		1	320	7.36	26.62	5	5.05	5.55	4
		1	354	25.15	34.41	6	24.67	4.22	5
		1	368	14.22	37.48	2	12.90	4.87	1
		1	404	22.08	34.91	2	22.06	4.28	1
		1	444	6.25	22.08	4	5.60	4.17	3
		1	472	4.99	29.69	5	5.55	4.84	4
		1	490	6.68	36.75	4	5.34	5.11	3
		1	556	11.39	38.31	4	11.92	6.86	3
		2	72	4.36	339.82	7	5.99	4.50	5
		2	98	22.41	35.42	4	28.63	4.41	3
		5	24	33.33	38.20	5	59.71	8.96	4
		5	66	32.86	28.31	4	47.68	5.41	3
		5	88	57.69	34.54	7	47.94	3.72	6
		5	100	56.56	21.92	6	69.23	3.80	5
		5	156	25.81	38.86	4	30.50	5.72	3
		5	160	32.09	29.97	6	34.84	6.90	5
Uncon	Uncon	1	64	24.14	46.79	4	14.75	3.67	3
2	2	1	96	20.84	48.08	3	18.25	4.03	2
Cons	Cons	1	156	12.24	47.18	4	9.47	4.07	3
		1	160	19.91	44.43	3	17.69	3.78	2
		1	232	27.22	41.70	2	20.22	3.33	1
		1	238	7.09	35.97	7	6.00	3.45	6
		1	330	21.64	41.33	4	15.04	2.78	3
		1	366	25.74	38.76	4	18.03	2.76	3
		1	382	25.67	45.57	3	19.21	4.00	2
		1	464	10.09	40.13	4	8.70	3.90	3
		1	544	16.12	45.61	5	13.59	4.07	4
		2	118	36.13	43.08	3	38.86	4.55	2
		5	94	26.74	45.99	6	29.40	2.25	5
		5	96	43.39	35.91	5	22.23	1.73	4
		5	104	56.62	33.28	12	36.98	2.12	11
		5	116	34.25	47.39	5	27.92	3.72	4

Table A.4 – Summary for Cons2Uncon and Uncon2Cons samples in Panel C, Table 8.
This table presents the average quoted spread (in bps and current tick) for assets in the Cons2Uncon and Uncon2Cons groups from Panel C, Table 8. The post-tick constraint level is based on the post-tick, while the current tick constraint level refers to the pre-period tick (pre-tick) and post-period tick (post-tick). Notably, all Cons2Uncon assets under the post-tick constraint rule are identified as Uncon2Uncon under the current tick rule. The quoted spread is averaged across pre- and post-periods for each asset pair. Tick size dp refers to the decimal places for tick size, such as 0.01 for 2 dp.

				Pre			Post		
Post tick constraint level	Current tick constraint level	Event id	Asset id	Quoted spread (bps)	Quoted spread (pre tick)	Tick size dp	Quoted spread (bps)	Quoted spread (post tick)	Tick size dp
Cons	Uncon	1	190	9.61	27.26	4	9.89	5.13	3
2	2	1	320	7.36	26.62	5	5.05	5.55	4
Uncon	Uncon	1	444	6.25	22.08	4	5.60	4.17	3
		1	472	4.99	29.69	5	5.55	4.84	4
		1	490	6.68	36.75	4	5.34	5.11	3
		1	556	11.39	38.31	4	11.92	6.86	3
		2	72	4.36	339.82	7	5.99	4.50	5
		2	98	22.41	35.42	4	28.63	4.41	3
Uncon	Uncon	1	96	20.84	48.08	3	18.25	4.03	2
2	2	1	156	12.24	47.18	4	9.47	4.07	3
Cons	Cons	1	232	27.22	41.69	2	20.22	3.33	1
		1	366	25.74	38.76	4	18.03	2.76	3
		1	382	25.67	45.57	3	19.21	4.00	2
		1	544	16.12	45.61	5	13.59	4.07	4
		2	118	36.13	43.08	3	38.86	4.55	2

E Analysis of Tick Size Changes: Event-Level and Pooled Regressions

This section analyzes pooled tick size increases and decreases, as well as individual events. In the baseline model, which covers all tick size increasing and decreasing assets, we control for event and asset fixed effects. In the single event regression, where each event is analyzed separately, we control for asset pair fixed effects. Standard errors are clustered by event-asset and date in the baseline model, and by asset and date in the single event model.

Table A.5 – Impact of Tick Size Increase on Market Quality for Six Tick Size Increase Events
This table show the coefficient on the interaction term of $Treat \times Post$ for tick size increasing events. *Quoted Spread*, *Effective Spread* and *Short-term volatility* are measured in bps. *Realized spread* is measured in bps with the lead time of 30 seconds. *LnVolume* is the logarithm for volume in USD. *Trades* is measured in 1,000. For ease of exposition, we have included number of treated assets, number of control assets, the number of observations only for regressions using *LnDepth* as the dependent variable. The number of observations varies slightly across dependent variables. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Baseline controls the fixed effect of event and asset, while for single event we control the fixed effect of asset pair. All dependent variables are winsorized to the 95th percentile. Robust standard errors are reported in parentheses, which control the event-asset (asset pair) and date in the baseline (single event) model.

	Baseline	okex 2021/3/18	binance 2021/8/26	binance-us 2023/3/2	okex 2022/6/1	okex 2021/8/2	okex 2022/7/28
Quoted	-0.48	-3.93	-0.75	4.94**	-3.63	-0.74	-0.84
spread	(0.53)	(3.45)	(0.52)	(2.07)	(3.02)	(0.00)	(1.63)
Effective	0.03	-2.08	-0.2	4.79*	0.24	0.42	-2.74**
spread	(0.51)	(1.53)	(0.53)	(2.54)	(2.51)	(0.28)	(1.11)
Realized	-0.57	-1.78	-0.14	4.05**	-0.35	-1.28	-4.12***
spread(30)	(0.45)	(2.24)	(0.50)	(1.99)	(1.69)	(0.00)	(0.94)
LnDepth	0.74***	0.74*	0.64***	0.98***	1.02***	1.38*	0.90***
	(0.04)	(0.35)	(0.05)	(0.15)	(0.27)	(0.11)	(0.09)
LnVolume	0.02	0.28*	0.09*	-0.14*	0.04	0.40**	-0.02
	(0.04)	(0.13)	(0.05)	(0.08)	(0.17)	(0.01)	(0.08)
Short-term	0.75***	0.18	0.51***	1.58***	0.9	0.68	1.13***
volatility	(0.10)	(0.35)	(0.06)	(0.50)	(0.75)	(0.14)	(0.31)
Obs.	3,467,384	24,768	2,344,568	297,216	123,840	8,256	668,736
Treat	420	3	284	36	15	1	81
Control	420	3	284	36	15	1	81
FE	Event-Asset				Asset		

Table A.6 – Impact of Tick Size Decrease on Market Quality for Seven Tick Size Reduction Events

This table shows the coefficient on the interaction term of $Treat \times Post$ for tick size decreasing events. *Quoted Spread*, *Effective Spread* and *Short-term volatility* are measured in bps. *Realized spread* is measured in bps with the lead time of 30 seconds. *LnVolume* is the logarithm for volume in USD. *Trades* is measured in 1,000. Baseline is the result of all seven decreasing events. All dependent variables are winsorized to the 95th percentile. Robust standard errors are reported in parentheses, which control the event-asset (asset pair) and date in the baseline (single event) model. For ease of exposition, we have included number of treated assets, number of control assets, the number of observations only for regressions using *LnDepth* as the dependent variable. The number of observations varies slightly across dependent variables. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Baseline controls the fixed effect of event and asset, while for single event control the fixed effect of asset pair.

	Baseline	okex 2021/3/18	binance 2021/8/26	binance-us 2023/3/2	okex 2022/6/1	okex 2021/8/2	okex 2022/7/28	kucoin 2023/1/18
Quoted	-13.09***	-1.56	-1.73	-24.89***	-20.08*	-23.49***	-38.77*	-9.27*
spread	(2.97)	(3.78)	(1.94)	(6.83)	(10.95)	(6.24)	(19.21)	(5.36)
Effective	-6.83**	2.84*	-0.97	-17.48***	-32.38***	-7.91**	63.28	-6.71**
spread	(3.00)	(1.42)	(1.32)	(5.80)	(8.72)	(3.51)	(71.13)	(2.58)
Realized	-3.95	1.34	1.53	-10.59*	-20.03**	-5.74*	71.92	-6.48**
spread(30)	(3.02)	(1.33)	(1.21)	(5.29)	(9.84)	(3.32)	(72.14)	(2.41)
LnDepth	-0.67***	-0.67***	-0.79***	-1.34***	-0.81***	-0.87***	-1.21***	-0.38***
	(0.05)	(0.15)	(0.08)	(0.13)	(0.14)	(0.12)	(0.22)	(0.08)
LnVolume	0.11**	0.17	-0.06	-0.01	0.39***	0.25***	0.18	-0.02
	(0.05)	(0.18)	(0.04)	(0.10)	(0.13)	(0.09)	(0.30)	(0.08)
Short-term	-1.68***	-1.05*	-1.65***	-1.79***	-6.38***	-0.88*	-1.77**	-1.05**
volatility	(0.28)	(0.49)	(0.15)	(0.47)	(1.29)	(0.51)	(0.71)	(0.45)
Obs.	3,582,500	49,536	693,232	181,632	338,496	627,164	123,840	1,568,600
Treat	434	6	84	22	41	76	15	190
Control	434	6	84	22	41	76	15	190
FE	Event-Asset				Asset			

F Robustness tests

Table A.7 – Market quality for tick size changing assets with matching pairs
This table presents the market quality metrics for all tick size changing assets with matching pairs listed on exchanges where the tick size did not change. The variables averaged across different groups, three weeks before and after the tick size change, and measured at 15-minute intervals. *Quoted spread* is the time-weighted relative quoted spread and measured in bps and current tick. *Effective spread* is volume-weighted effective spread and measured in bps. *Realized spread*is volume-weighted realized spread and is measured in bps. We use uniform 30s and 60s as X-second time horizons across all currency pairs. *Depth* is the 1,000 dollar volume quoted at the best prices. We estimate the time-weighted *Depth* in a 15-minute interval. *Volume* is the 15-minute total trading volume in $100,000. *Short-term volatility* is the the volatility of midpoint-to-midpoint returns calculated every 15 minutes and measured in bps. *Volatility* is the currency-time high-low price range scaled by the high-low midpoint in percent. *Trades* is the number of trades in 15-min interval. *Volume share* and *Trades share* represent the proportion of total volume and trades, respectively, occurring in the sample exchanges. Standard errors are reported beneath the mean values. The column 'Diff.' reports the difference in means before and after the tick size change. The 'Diff' for all variables are all significant based on a two-tailed t-test at 1% levels.

	Assets with increasing tick sizes			Assets with decreasing tick sizes		
	Pre	Post	Diff	Pre	Post	Diff
Quoted	13.98	14.67	0.69	47.68	34.25	-13.43
Spread (bps)	(13.00)	(12.50)		(51.46)	(45.29)	
Effective	13.01	13.40	0.40	35.41	29.38	-6.03
Spread (bps)	(16.98)	(25.33)		(52.30)	(55.60)	
Realized	3.03	2.75	-0.28	16.79	13.53	-3.26
Spread(30s, bps)	(17.56)	(24.73)		(44.15)	(47.86)	
Realized	3.01	2.85	-0.16	16.51	13.23	-3.29
Spread(60s, bps)	(18.80)	(24.67)		(46.04)	(48.54)	
Depth	4.53	10.85	6.32	4.76	1.26	-3.50
($1,000)	(23.92)	(35.10)		(8.70)	(1.77)	
Volume	3.52	3.89	0.37	0.29	0.67	0.37
($100,000)	(14.00)	(13.54)		(1.23)	(3.11)	
Short-term	2.36	2.91	0.55	6.37	5.49	-0.88
volatility(bps)	(1.48)	(2.29)		(8.95)	(9.17)	
Volume	43.91	42.44	-1.47	24.57	26.59	2.02
share (%)	(30.56)	(31.21)		(26.63)	(26.67)	
Trades	49.17	46.02	-3.15	30.28	31.96	1.69
share (%)	(29.65)	(29.52)		(24.50)	(24.32)	
Volatility	0.73	0.75	0.02	0.64	0.72	0.08
(%)	(0.59)	(0.65)		(0.70)	(0.66)	
Trades	4.00	3.94	-0.07	0.47	0.78	0.31
(100#)	(11.30)	(10.66)		(0.95)	(1.60)	

Table A.8 – Robustness Test for DiD Analysis of Tick Size Decreases by Post-leeway in Pre Tick

This table presents the robustness test for Panel C in Table 10 and Panel C in Table 11. Panel A presents the results for 'Constrained to Unconstrained' assets from Panel C of Table 10, which are divided into 'True' and 'False' groups based on whether the asset's post-leeway is less than three in pre-tick size. Panel B presents the results for 'Constrained to Unconstrained' assets from Panel C of Table 11, which are divided into 'True' and 'False' groups based on whether the asset's post-leeway is less than three in pre-tick size. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, which control for event-asset (exchange-asset) and date in Panel A (B), are reported in parentheses. For ease of interpretation, the number of treated and control assets, as well as the number of observations, is provided only for regressions using depth for Panel A, and trade share for Panel B as the dependent variable. The number of observations varies slightly across dependent variables. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

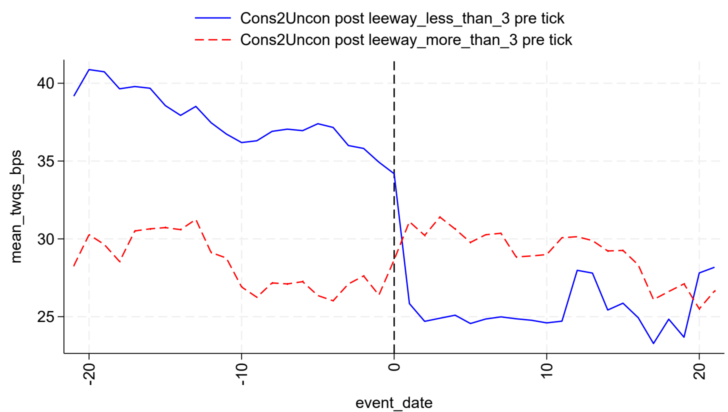
	Panel A: For 'Cons2Uncon' in tick size decreasing within exchanges, post leeway less than 3 pre ticks		Panel B: For 'Cons2Uncon' in tick size decreasing across exchanges, post leeway less than 3 pre ticks	
	True	False	True	False
Quoted	-17.54***	8.64***	-6.61**	4.49
Spread	(3.13)	(2.72)	(3.27)	(2.87)
Efficient	-9.45***	1.61	-4.36*	2.65
Spread	(2.98)	(2.16)	(2.28)	(2.11)
Realized	-7.19**	2.97*	-1.91	6.02*
Spread (30s)	(2.77)	(1.69)	(1.76)	(3.03)
Realized	-7.41***	2.84	-2.03	5.81*
Spread (60s)	(2.76)	(1.75)	(1.69)	(2.98)
LnDepth	-0.88***	-0.40***	-0.88***	-0.57***
	(0.07)	(0.09)	(0.11)	(0.16)
LnVolume	0.07	0.07	0.02	-0.09
	(0.07)	(0.08)	(0.21)	(0.11)
Short term	-1.37***	-1.69***	-0.67**	-0.79
volatility	(0.39)	(0.46)	(0.27)	(0.77)
Volume			4.60***	-3.84***
share			(1.30)	(1.16)
Trades			4.93***	-7.82***
share			(1.13)	(2.02)
Obs.	1,931,768	652,184	757,049	238,240
Treat	234	79	63	25
Control	234	79	113	31
FE	Event-Asset		Exchange-Asset	

Table A.9 – Robust Test for DiD Analysis of Tick Size Increases by Pre-leeway in Post Tick. This table presents the robust test for Panel C in Table 5 and Panel C in Table 7. Panel A presents the results for 'Unconstrained to Constrained' assets from Panel C of Table 5, which are divided into 'True' and 'False' groups based on whether the asset's pre-leeway is less than 3 post tick. Panel B presents the results for 'Unconstrained to Constrained' assets from Panel C of Table 7, which are divided into 'True' and 'False' groups based on whether the asset's pre-leeway is less than 3 post tick. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, which control for event-asset (exchange-asset) and date in Panel A (B), are reported in parentheses. For ease of interpretation, the number of treated and control assets, as well as the number of observations, is provided only for regressions using depth for Panel A, and trades share for Panel B as the dependent variable. The number of observations varies slightly across dependent variables.***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

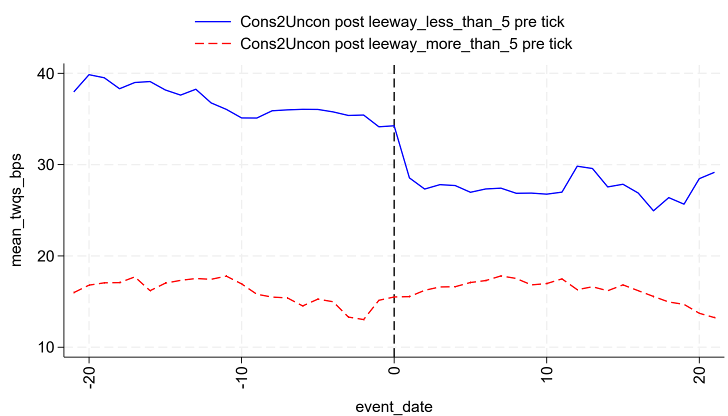
	Panel A: For 'Uncon2Cons' in tick size increasing within exchanges, pre-leeway less than 3 post tick.		Panel B: For 'Uncon2Cons' in tick size increasing across exchanges, pre-leeway less than 3 post tick.	
	True	False	True	False
Quoted	1.74***	-3.09***	4.16***	-0.14
Spread	(0.62)	(0.80)	(1.06)	(1.26)
Efficient	1.92***	-1.29**	2.46***	-0.5
Spread	(0.51)	(0.60)	(0.88)	(1.15)
Realized	0.24	-1.85***	1.82***	-0.24
Spread (30s)	(0.33)	(0.55)	(0.67)	(0.92)
Realized	0.25	-1.80***	1.71**	0.01
Spread (60s)	(0.32)	(0.55)	(0.66)	(0.93)
LnDepth	1.10***	0.51***	0.80***	0.21
	(0.06)	(0.07)	(0.12)	(0.20)
LnVolume	-0.03	-0.09	-0.21*	-0.06
	(0.02)	(0.10)	(0.12)	(0.12)
Short term	0.84***	0.64***	0.70***	0.58***
volatility	(0.13)	(0.13)	(0.19)	(0.16)
Volume			-4.97***	-2.37*
share			(1.07)	(1.20)
Trades			-5.28***	-5.05***
share			(1.23)	(1.20)
Obs.	1,675,968	404,544	1,209,036	210,432
Treat	203	49	107	19
Control	203	49	187	32
FE	Event-Asset		Exchange-Asset	

Figure A.5 – The average quoted spread for constrained to unconstrained assets across exchanges, categorized by the post-leeway measured in pre tick.
This figure illustrates the average quoted spread for 'Constrained to unconstrained' assets (with the unconstrained level based on the current tick), categorized by post-leeway measured in pre-tick. The post-leeway thresholds are set at 3, 5, and 7 pre ticks. The horizontal axis, labeled event_date, represents the event date, with the tick size change day marked as 0. The vertical axis shows the mean quoted spread in bps, averaged daily within the group. The solid blue line represents assets with limited post-leeway before the tick size decrease, while the dashed red line represents assets with sufficient post-leeway.

A: 3 pre tick.



B: 5 pre tick.



C: 7 pre tick.

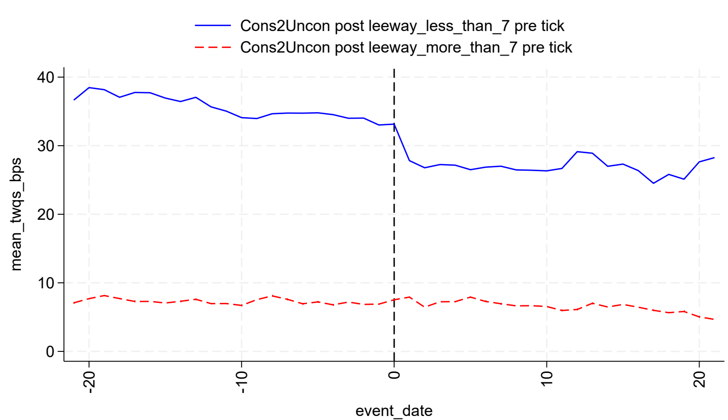
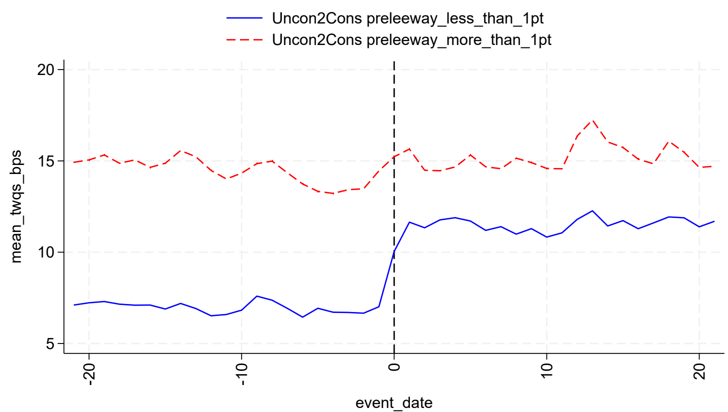
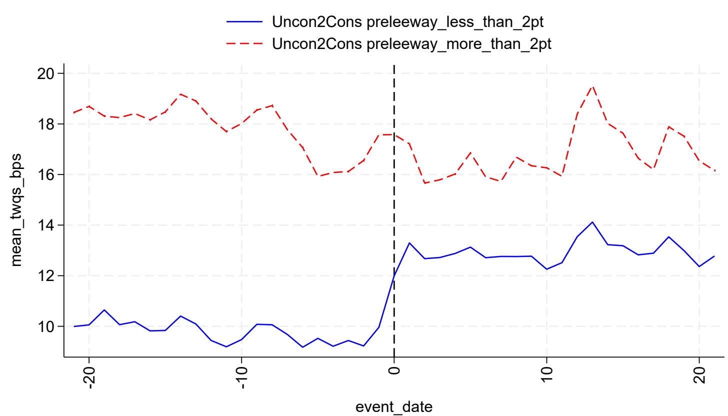


Figure A.6 – The average quoted spread for unconstrained to constrained assets across exchanges, categorized by the pre-leeway measured in post tick.
This figure illustrates the average quoted spread for 'Unconstrained to Constrained' assets (with the unconstrained level based on the current tick), categorized by pre-leeway measured in post-tick. The pre-leeway thresholds are set at 1, 2, and 3 post ticks. The horizontal axis, labeled event_date, represents the event date, with the tick size change day marked as 0. The vertical axis shows the mean quoted spread in bps, averaged daily within the group. The solid blue line represents assets with limited pre-leeway before the tick size increase, while the dashed red line represents assets with sufficient pre-leeway.

A: 1 post tick.



B: 2 post tick.



C: 3 post tick.

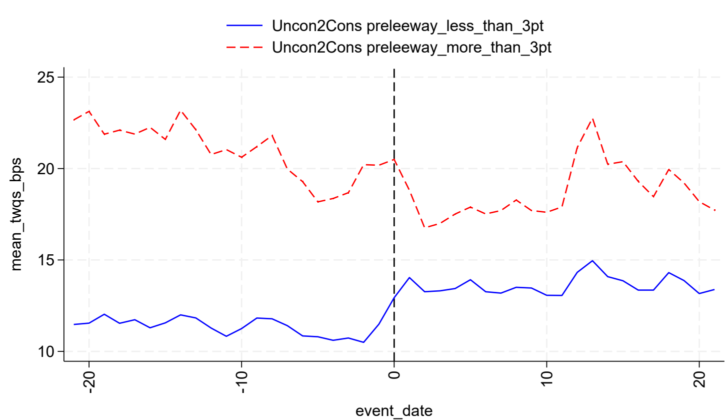


Table A.10 – Within-Exchange triple DiD Analysis of Tick Size changing.
This table presents the coefficients of the interaction term $Treat \times Post \times DummyVar$ for tick size changing intensity in a triple DiD analysis within exchanges. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, controlling for exchange-asset and date, are reported in parentheses. For ease of interpretation, we have included the number of treated assets, control assets, and observations only for regressions using trades share as the dependent variable. The number of observations vary slightly across dependent variables. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regression models include exchange-asset fixed effects.

	Tick size increase			Tick size decrease		
Original Results	Tab 5, Panel A	Tab 5, Panel B	Tab 5, Panel C	Tab 10, Panel A	Tab 10, Panel B	Tab 10, Panel C
Dummy Var	Cons	Uncon2Uncon	TRUE	Cons	Cons2Cons	TRUE
Quoted	5.13***	-3.52***	3.65***	-7.52	-61.00***	-27.70***
Spread	(1.63)	(1.17)	(1.02)	(9.40)	(17.40)	(4.64)
Efficient	4.52*	-3.26***	2.45***	-8.78**	-17.50**	-12.93***
Spread	(2.37)	(0.98)	(0.81)	(3.47)	(8.21)	(4.42)
Realized	4.21***	-1.71**	1.53***	-6.19**	-8.8	-11.72***
Spread (30s)	(1.50)	(0.78)	(0.52)	(3.08)	(5.86)	(4.12)
Realized	4.34***	-1.33*	1.56***	-6.18**	-8.91	-11.59***
Spread (60s)	(1.43)	(0.78)	(0.52)	(3.07)	(5.87)	(4.12)
LnDepth	1.20***	-0.69***	0.70***	-0.68***	-1.07***	-0.57***
	(0.21)	(0.07)	(0.09)	(0.11)	(0.15)	(0.11)
LnVolume	-0.34	0.19***	-0.06	-0.01	0.61**	0.06
	(0.27)	(0.05)	(0.05)	(0.12)	(0.26)	(0.10)
Shotr term	-0.57**	-0.11	-0.04	1.14*	1.28	0.85
volatility	(0.26)	(0.21)	(0.21)	(0.62)	(1.34)	(0.54)
Obs.	3,467,384	3,401,336	2,080,512	3,582,500	2,757,192	2,583,952
Treat	420	412	252	434	334	313
Control	420	412	252	434	334	313
FE			Exchange-Asset			

Table A.11 – Cross-Exchange triple DiD Analysis of Tick Size changing.
This table presents the coefficients of the interaction term $Treat \times Post \times DummyVar$ for tick size changing intensity in a triple DiD analysis across exchanges. All dependent variables are winsorized to the 95th percentile for each asset pair. Robust standard errors, controlling for exchange-asset and date, are reported in parentheses. For ease of interpretation, we have included the number of treated assets, control assets, and observations only for regressions using trades share as the dependent variable. The number of observations vary slightly across dependent variables. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. All regression models include exchange-asset fixed effects.

	Tick size increase				Tick size decrease			
Original Results	Tab 7, Panel A	Tab 7, Panel B	Tab 7, Panel C	Tab 9	Tab 11, Panel A	Tab 11, Panel B	Tab 11, Panel C	Tab 12
Dummy Var	Cons	Uncon2 Uncon	TRUE	Dominant	Cons	Cons2 Cons	TRUE	Dominant
Quoted	1.72	0.28	3.79**	-4.68**	-3.54	-51.74***	-14.30***	-82.09***
Spread	(2.68)	(2.76)	(1.64)	(1.85)	(9.94)	(17.18)	(4.47)	(22.95)
Efficient	0.95	1.88	1.78	-3.74**	-1.74	-22.50***	-7.72**	-18.58**
Spread	(1.85)	(2.77)	(1.38)	(1.66)	(7.05)	(4.99)	(3.44)	(8.67)
Realized	-0.18	1.22	1.66	-2.39*	-1.97	-7.91***	-7.46**	-13.43***
Spread (30s)	(0.76)	(2.25)	(1.08)	(1.42)	(5.51)	(2.97)	(3.07)	(4.18)
Realized	0.03	1.29	1.48	-2.14	-1.9	-7.68***	-7.23**	-12.99***
Spread (60s)	(0.79)	(2.28)	(1.07)	(1.38)	(5.42)	(2.86)	(2.99)	(4.05)
LnDepth	1.20***	-0.44**	0.61***	0.11	-0.26	-1.14***	-0.52***	0.26
	(0.29)	(0.22)	(0.17)	(0.16)	(0.32)	(0.20)	(0.18)	(0.34)
LnVolume	0.1	-0.06	0.17	0.47**	-0.07	1.04***	-0.21	0.29
	(0.54)	(0.28)	(0.20)	(0.20)	(0.68)	(0.33)	(0.32)	(0.52)
Short term	-0.17	-0.41*	0.04	-0.92***	-0.57	0.08	-0.07	-1.28
volatility	(0.34)	(0.24)	(0.27)	(0.31)	(1.55)	(0.57)	(0.52)	(0.87)
Volume	4.43	2.61	-1.51	10.04***	9.82**	14.84***	0.64	10.94
share	(2.81)	(2.25)	(2.10)	(3.05)	(4.85)	(4.26)	(3.80)	(7.80)
Trades	-4.15	2.34	-4.03*	9.62***	-0.9	17.37***	2.63	13.88**
share	(7.19)	(1.92)	(2.32)	(3.42)	(5.43)	(3.84)	(3.63)	(6.76)
Obs.	2,061,767	1,975,079	1,419,468	1,427,751	1,347,888	1,135,035	995,289	139,746
Treat	182	176	126	125	125	101	89	12
Control	319	304	219	222	203	175	153	22
FE	Exchange-Asset							