Latency Arbitrage and Market Liquidity*

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December 14, 2022

Abstract

There is an increasing concern that fast arbitrageurs cause market making more expensive by picking off quotes before the liquidity provider was able to revise. This paper shows that adverse selection and liquidity improves after restricting aggressive proprietary trading. Bid-ask spread declines by 11% and adverse selection costs declines by 21%. Liquidity providers earn higher realized spreads and quote higher volumes at better prices. I further identify cross-exchange latency arbitrage and find that the restriction eliminates more than half of toxic arbitrage trades. Market makers benefit from a lower likelihood of being sniped when public information arrives, and are hence subject to lower adverse selection costs. The findings suggest that restricting latency arbitrage improves liquidity by reducing toxic arbitrage.

Keywords: adverse selection; latency arbitrage; toxic arbitrage; passive liquidity protection.

*First Version: October 30, 2020.

†Email: chengcheng.qu@sbs.su.se. I would like to thank my supervisors Björn Hagströmer, Lars Nordén, and Michał Dzielinski for their patient guidance. I am also grateful to Darya Yuferova, Carsten Tanggaard, Richard Payne, Jonathan Brogaard, Sean Foley, Markus Baldauf, Jean-Edouard Colliard, Albert Menkveld, Petter Dahlström, Dagfinn Rime, and participants at the SHoF National PhD Workshop and NFN PhD Workshop for their valuable comments.

1 Introduction

Fast trading techniques allow arbitrageurs to profit from short-lived price differences between related securities by picking off stale quotes before liquidity providers can adjust their quotes to public information. This arbitrage strategy, known as latency arbitrage, raises concerns that fast trading firms magnify adverse selection and liquidity costs even when fundamental information is symmetrically known (Budish, Cramton, and Shim, 2015; Foucault, Kozhan, and Tham, 2017). Aquilina, Budish, and O'Neill (2022) estimate that eliminating latency arbitrage will reduce liquidity costs by 16.7% marketwide.

As one way to address concerns over latency arbitrage, exchanges can add a message delay on market orders. This approach, also known as a speed bump, is introduced to Investors Exchange (IEX), Toronto Stock Exchange (TSX) Alpha, and Eurex. Foucault et al. (2017) suggest that slowing down fast arbitrageurs relative to liquidity providers reduces the fraction of toxic arbitrage hence lowering adverse selection and liquidity costs. As another approach, the pan-European stock exchange Aquis bans proprietary traders from taking liquidity. Proprietary traders are mainly high-frequency trading firms managing their own money at their own risk. After the ban, proprietary traders on Aquis can only trade passively via limit orders as designated liquidity providers (DLPs). Aquis' ban grants liquidity providers sufficient time to revise stale quotes. The design is analogous to an infinitely long delay in market orders from fast traders to mitigate adverse selection.

I find that liquidity improved in the first four weeks after the ban for a sample of the 200 most traded stocks in 13 European markets[1]. Round-trip transaction costs, measured as the bid-ask spreads, narrowed by 11% from 15.4 bps to 13.7 bps on Aquis. The fraction of quoted depth post at the European best bid and offer (EBBO) prices from Aquis more than doubled. The liquidity improvement can be attributed to a 16% drop in adverse selection costs from 5.7 bps to 4.8 bps on Aquis. The improvements in liquidity and

[1]The markets are London, Paris, Frankfurt, Zurich, Amsterdam, Madrid, Milan, Oslo, Helsinki, Lisbon, Brussels, Copenhagen, and Stockholm.

adverse selection are persistent when compared with a benchmark group of exchanges without the ban. Using a difference-in-difference approach, I estimate a 21% (1.2 bps) drop in adverse selection costs on Aquis relative to exchanges without the ban. Profits for liquidity proviSion increased by 66% (1.3 bps) and the total transaction costs for liquidity traders, measured as the effective spread, remained unchanged. These findings show that restricting fast arbitrageurs from taking liquidity protects liquidity suppliers from being sniped and mitigates adverse selection costs, hence improving market liquidity. The results are in line with theoretical predictions of Foucault et al. (2017), Brolley and Cimon (2020), and Baldauf and Mollner (2020).

Surprisingly, although Aquis lost substantial trading volume from aggressive proprietary trading, the total traded value at the exchange surged by 60% from 291.4 million to 465.3 million EUR one month after the ban. The market share of Aquis in displayed trading on all listed stocks in 13 European markets increased from 0.73% to 1.14% during the same period as illustrated in **Figure 1**[2]. The increase in trading volume deviates from the speed bump model in Brolley and Cimon (2020) who predict that an infinitely long delay on all market orders can drive away liquidity takers leading to no trades on the delayed venue. This discrepancy is due to that Aquis' ban restricts only proprietary trading but not client-based brokers or institutional traders. The later group at Aquis benefits from improved liquidity as latency arbitrageurs would intercept liquidity to end investors otherwise. Thus, Aquis' ban benefits not only the liquidity providers but also brokers and institutional investors who require liquidity.

Firm-level trading data from the Swedish equity market reveals that aggressive proprietary trading at Aquis dropped to almost 0 the next day after Aquis announced the schedule to introduce the trading ban. Following this clear effect restricting latency arbitrage, I compare the fraction of cross exchanges toxic arbitrage in which Aquis fails to update stale quotes in time before and after the ban. I decompose the fraction of

[2]Data source: Cboe European Equities Market Share https://markets.cboe.com/europe/equities/market_share/market/. Market share data are aggregated from all displayed trading in 13 markets, which are London, Paris, Frankfurt, Zurich, Amsterdam, Madrid, Milan, Oslo, Helsinki, Lisbon, Brussels, Copenhagen, and Stockholm.

cross exchanges toxic arbitrage into the fraction of toxic arbitrage opportunities to all arbitrage opportunities, which remained unchanged; and the probability of successfully exploiting a toxic arbitrage opportunity with a trade, which declined by almost two-thirds in a difference-in-difference comparison. Accordingly, the ban alleviates adverse selection through the speed race channel that arbitrageurs face a lower chance to snipe stale quotes and liquidity providers see a higher probability to update stale quotes and avoid adverse selection. I find no evidence of worse adverse selection at non-banned exchanges.

Is it really beneficial to have lower latency and price adjustment 1 millisecond faster when arbitrageurs have a significant speed advantage over market makers and liquidity traders? The popular novel *Flash Boy* by Michael Lewis puts the downside of latency arbitrage under the spotlight. Meanwhile, proposals to protect liquidity from latency arbitrage, such as the speed bump at the "Flash Boy" exchange, IEX, or trading ban at Aquis, receive both support and opposing voices from the market. Voice for leveling the playing field argues that latency arbitrage triggers inefficient speed arm races to snipe stale quotes due to asynchronous price adjustment. In response to higher adverse selection costs, liquidity providers will withdraw liquidity or charge higher spreads to cover the loss to latency arbitrageurs. Ultimately, end investors receive lower liquidity and pay higher costs. In the meantime, exchanges worry about losing trading volume from arbitrageurs and lower revenue after restricting latency arbitrage. Protecting market makers from sniping benefits liquidity provision, but investors also worry that market makers will take advantage of the "last look" opportunity and actively withdraw unfavorable quotes, leading to worse or fading liquidity.

This paper contributes new evidence to current research on latency arbitrage, market liquidity, and market design. First, this study explores a ban on aggressive proprietary trading as an alternative solution to latency arbitrage and estimates the liquidity effects of the ban for the first time. The study provides additional evidence for the efficiency and complexity of passive liquidity protection mechanisms which extend to membership bans, trading restrictions, and speed bumps.

Second, this study uses a clear event to estimate the direct liquidity impact of limiting fast aggressive trading. The previous studies concerning the liquidity impacts of a speed bump document mixed results. Chen et al. (2017) find that liquidity gets more expensive after TSX Alpha introduces a speed bump. In the same event, Anderson et al. (2018) find that the speed bump is harmless to local and marketwide liquidity. Moreover, both order fill rates and execution sizes increase on TSX Alpha. These contradictory results are likely due to the combined effects of introducing an inverted fees scheme and a speed bump simultaneously, as one is aimed to encourage liquidity taking and the other to encourage liquidity making. Aquis Exchange has a rather consistent market structure: the fee structure and designated liquidity providers scheme remain unchanged since its launch in 2013. Therefore, the investigation based on Aquis' event helps to identify the liquidity impact more clearly and to resolve the contradictions.

Third, this study extends the literature on exchanges differentiation, especially exchanges that match liquidity providers with liquidity traders at a lower adverse selection and liquidity costs. The trading ban makes the exchange more attractive to both liquidity providers and institutional investors. Investigations on this market design add to uncover the spillover effects of the ban on other exchanges and to understand factors attracting traders to exchange with restrictions.

2 Previous research

2.1 Latency arbitrage

Due to communication and order processing delays, market participants differ in their abilities to respond quickly to news. Price changes that are asynchronous across exchanges create arbitrage opportunities that last for milliseconds that only fast traders can exploit. Budish et al. (2015) refer to this type of arbitrage as latency arbitrage. They show that fast traders snipe stale quotes before liquidity providers can cancel and update their quotes. Their model shows that latency arbitrage fuels inefficient speed arms races for speed. Shkilko and Sokolov (2020) show that removing fast traders' speed advantage reduces adverse selection and trading costs either temporally or in the long term.

Foucault et al. (2017) note that fast arbitrage promotes price efficiency at the costs of higher adverse selection risks on market makers and more expensive liquidity costs on investors. Menkveld and Zoican (2017) also show that fast traders snipe quotes and intercept liquidity reaching investors at low latency exchange. Aquilina et al. (2022) estimate that latency arbitrage profits are 0.49 bps on average. 55% of the profits are distributed among the top three fast trading firms. The profits come at higher liquidity costs (0.68 bps) born by slow traders.

2.2 Restrictions on latency arbitrage

Theoretical models on latency arbitrage predict that a speed bump can level the playing field of fast and slow traders at the exchange and thus mitigates adverse selection (Budish et al., 2015; Baldauf and Mollner, 2020; Brolley and Cimon, 2020). Budish et al. (2015) suggest that a deterministic delay on marketable orders protects liquidity suppliers from adverse selection if the length of the delay is long enough for liquidity providers to revise stale quotes before arbitrageurs can hit them. The ban at Aquis resembles a delay of infinite length on aggressive proprietary orders and grants liquidity providers sufficient time to revise stale quotes. Accordingly, I expect that the ban mitigates adverse selection and improves liquidity on Aquis.

Empirical investigations on speed bump adaption at Toronto Stock Exchange Alpha (Anderson et al., 2018)[3], IEX (Hu, 2019), and Eurex (Le Moign, 2022) report improvement in liquidity and lower spreads at the delayed exchange. Brolley and Cimon (2020) predict that informed traders will switch to non-delayed exchanges to avoid message delay on marketable orders. Meanwhile, liquidity providers will find it more attractive to trade

[3]While Chen et al. (2017) find worse fading liquidity and market quality after the speed bump

with fewer informed traders at the delayed exchange. Given the segmentation of informed and uninformed traders, the delayed exchange benefits from lower adverse selection and attracts more liquidity while the non-delay ones can be worse off. The opposite impacts on treated and non-treated exchanges suggest a different-in-differences setup to test the hypothesis that:

Hypothesis 1 *Banning aggressive proprietary traders mitigates adverse selection and improves liquidity at the treated exchange compared to other exchanges without a ban.*

Foucault et al. (2017) model that adverse selection increases with the fraction of toxic arbitrage opportunities and the likelihood that fast traders snipe stale quotes. The trading ban at Aquis restricts aggressive proprietary trading, allowing market makers to remove stale quotes before being sniped. In expectation, the ban does not affect new information arriving and has no impact on the fraction of toxic arbitrage opportunities. On the other hand, the ban diminishes the threat of sniping and lowers (boosts) the probability that a toxic arbitrage opportunity is terminated with a trade (quote). Therefore, market makers can update stale quotes and avoid being adversely selected by latency arbitrageurs.

Hypothesis 2 *The probability that a toxic arbitrage opportunity is terminated with a quote (trade) would increase (decrease) after the ban.*

Investigation on passive liquidity protection (PLP), in particular speed bump, and latency arbitrage is limited to Eurex's whitepaper on DAX index options. The whitepaper discloses that delaying aggressive orders by 1-3 milliseconds reduces latency arbitrage by 34%[4][5]. Protecting liquidity from latency arbitrage by banning aggressive proprietary traders is a more rigorous measure and I expect stronger declines in latency arbitrage and adverse selection after Aquis' ban.

[4]Eurex whitepaper on the passive liquidity protection: https://www.eurex.com/resource/blob/2716266/f139149fe08ef13fbe787ea361089b20/data/Whitepaper_Eurex_Passive_Liquidity_Protection.pdf

[5]The case study which releases impacts on latency arbitrage: https://www.eurex.com/resource/blob/2716274/9efc6eedbaa741093e84f923b86c1bdc/data/PLP_in_the_dax_index_option_case_study.pdf

2.3 Alternative liquidity protections

Budish et al. (2015) argue that latency arbitrage is rooted in the continuous trading mechanism which is widely adopted. They suggest replacing continuous trading with a frequent batch auction to latency arbitrage trades.Brunnermeier and Pedersen (2005) suggest that batch auction design alleviates predatory trading but its effects on encouraging liquidity provision are limited. However, recent empirical evidence is very limited on switching continuous limit order book to the batch auction. Brunnermeier and Pedersen (2005) also discuss alternative approaches including financial transactions taxes (Colliard and Hoffmann, 2017), minimum resting times requirement, and high message-to-trade ratio penalty (Friederich and Payne, 2015) to restrict latency arbitrage. Ait-Sahalia and Saglam (2017) find that these three alternative policies as well as pro rata priority or random allocation is unable to stimulate robust liquidity provision from high-frequent traders. Brolley and Zoican (2022) propose micro burst fees to protect liquidity by allocating speed race profits to exchange and liquidity providers.

3 Institutional details

The Aquis Exchange is a pan-European cash equity trading platform. It was established in October 2012 and launched as a multilateral trading facility (MFT) in November 2013. In 2016, Aquis operated a lit order book for more than 500 stocks, which were mainly constituents of the 13 major European indices. Aquis Exchange is not a listing venue and it mirrors the trading calendar, trading hours, quote currency, and tick size at the listing exchange. Since its establishment, Aquis differentiated itself from other trading venues with its subscription-based fee schedule, which charges members based on their message traffic instead of basis points commissions on trade value. A monthly subscription covers an average daily allowance of messages generated from order submissions, cancellations, modifications, or crossing. The top-tier subscription is entitled to unlimited message usage. Aquis pays no maker rebates but messages to post liquidity are free.

Given its small scale, Aquis relies on a few market makers to provide liquidity to institutional traders. However, fast arbitrageurs actively sniped their quotes, and market makers had to withdraw liquidity to prevent losing against snipers. On February 3, 2016, Aquis announced that a ban on aggressive proprietary trading would take effect on February 8, 2016, to protect liquidity provision. With the ban, Aquis members must report whether they conduct client business or proprietary trading. Proprietary traders must sign in Liquidity Provider Scheme and can only trade passively as designated liquidity providers (DLPs). If there is any violation, Aquis can either restrict the member's right to place orders or terminate the membership. The Designated Liquidity Providers Scheme has been initiated since 2013 at Aquis' launch. The scheme requires designated liquidity providers to post quotes of a minimum size of €5,000 on both bid and ask sides of the order book[6]. The obligation on quote price is within 1% best bid and offer prices at the listing exchange (also known as Primary Best Bid and Offer Price, PBBO) for at least 50% of the trading hours for one security[7][8]. No other structural change happened at Aquis in 2016.

4 Empirical evidences

4.1 Impacts on liquidity

To identify the impact of banning aggressive proprietary trading on market liquidity, I adapt the difference-in-difference (diff-in-diff) approach and compare the liquidity

[6]The obligation is €5,000 on Bats and 30,000 SEK, approximately €3,000, on Nasdaq OMX Stockholm.

[7]The 50% threshold is the minimum obligation given by the European Securities and Markets Authority (ESMA). The threshold is 90% on the London Stock Exchange (LSE) and 85% on Nasdaq OMX Stockholm. Bats has the same requirement for quoting time as Aquis, but the required spreads (0.25%) are tighter.

[8]The earliest list of Aquis DLPs that I can find is from 2018 when the DLPs were BNP Paribas Arbitrage SNC, Citadel Securities (Europe) Limited, Sun Trading International Limited, Tower Research Capital Europe Limited, Virtu Financial Ireland Limited, and XTX Markets Limited.

change on Aquis relative to exchanges without the ban using the following model:

$$y_{i,t,m} = \alpha_i + \beta_t + \gamma_m + \delta Treatment_m \times Post_t + \lambda X_{i,t} + \varepsilon_{i,t,m} \quad (1)$$

In **Equation 1**, the dependent variable $y_{i,t,m}$ denotes liquidity measure for stock i traded at exchange m on day t. The treatment dummy $Treatment_m$ equals 1 if exchange m is the Aquis Exchange, or 0 if one of the MTFs or listing exchanges. The event dummy $Post_t$ equals 1 for date t from February 8 to March 4, 2016. Therefore, the coefficient δ on the cross term $Treatment_m \times Post_t$ captures the liquidity change at the exchange banning aggressive proprietary traders in relative to exchanges without the ban. Stock-day level control variables $X_{i,t}$ include logarithmic total turnover of stock i on date t from all exchanges and daily average realized volatility of EBBO midprice in 5-minute intervals as stock-day level factors which affect marketwide liquidity. Finally, fixed effects α_i, β_t, and γ_m control heterogeneity across sample stocks, days, and exchanges.

In the empirical test, I use four weeks before and after the change as the event window. I set the cutoff date for the pre-event period to Tuesday, February 2, 2016, when the earliest media release on the Aquis' ban was available one day before Aquis' announcement via member notice on Wednesday, February 3, 2016[9][10]. The rule change took effect on Monday, February 8, 2016, which is the first day of my post-event period. Therefore, the pre-event period lasts from January 5 to February 1, 2016, and the post-event period from February 8 to March 4, 2016.

During the sample period, trades on Aquis concentrated on blue-chip stocks from the 13 major European market indices which are Amsterdam AEX 25, Brussels BEL 20, OMX Copenhagen 20, Frankfurt DAX 30, IBEX 35, OMX Helsinki 25, FTSE 100, FTSE/MIB 40, Oslo OBX 25, CAC 40, OMX Stockholm 30, Lisbon PSI 20, and SMI20. Among the 426 constituents, 423 of them are traded simultaneously on Aquis as well as

[9] Aquis to ban predatory HFTs, The Trade: https://www.thetradenews.com/aquis-to-ban-predatory-hfts/.

[10] Aquis Member Notice 0004: https://aquis-website-eu.s3.amazonaws.com/Aquis-Member-Notice-0004-Important-Changes-to-Terms-of-Membership.pdf.

other pan-European MTF exchanges. I select the 200 most traded stocks based on daily counts of trades in the pre-event period on listing exchanges. The stock BG Group plc was delisted from LSE due to acquisition on February 12, 2016, and I replace it with Alfa Laval AB, which is the most traded from the remaining stocks. No other stocks in the sample were affected by any index change or merger and acquisition event in the sample period. My final sample contains 3,973 stock-day observations in the period before[11] and 4,000 observations after the event. **Table 1** presents the composition of sample stocks by listing exchanges.

All the 200 sample stocks were traded on their listing exchanges and MTFs including Aquis, BATS, Chi-X, and Turquoise during the sample period. Exchanges except for Aquis consist of the non-banned benchmark group. Stock i traded at the treated and controlled exchanges are fundamentally the same. The only differences are the market designs. For the sample stocks, I calculate stock-date-exchange level liquidity measures from intraday trades and quotes from Refinitive Tick History (RTH) database. I drop trades generated from off-exchange trading, dark trading, block trading, and auctions when constructing liquidity measures.

The liquidity measures I construct in testing **Hypothesis 1** whether the ban mitigates adverse selection and improves liquidity on Aquis include time-weighted quoted spreads, volume-weighted effective spreads, volume-weighted realized spreads in 10-seconds, 1-minute, 5-minute intervals, and volume-weighted price impact in the same three time intervals. I also calculate the percentage share in EBBO depth volume of each exchange and for how many seconds EBBO quotes are available at the exchange. All spreads are relative to the midpoint of EBBO and in basis points (bps). To ensure that the daily observations are representative, I winsorize intraday outliers to 1% (99%) percentiles before aggregating daily average measures. **Table 2** presents the means, standard deviations, and medians of each liquidity measure by venues subgroups.

[11] No trades for 37 Swedish and 7 Finish stocks in the sample on January 6 because of the exchange holiday.

Figure 3 illustrates the level changes in liquidity on the treated and controlled exchanges after the ban. The level lines indicate the time-series averages of liquidity measures across 200 sample stocks for the treated (solid) and the controlled (dashed) venues. The changes in the differences between solid and dash lines illustrate simple difference-in-difference impacts on market liquidity.

The level changes show that liquidity on Aquis improved with narrower quoted spreads and effective spreads after the ban. This implies that it was cheaper to hit an order on the opposite side and to trade with a market order. Breaking down the effective spreads, I find that price impact significantly decreased and realized spreads slightly increased. The pattern implies that the adverse selection costs on liquidity makers dropped and the profits to them slightly increased. The net improvement in liquidity went together with lower price impact in that liquidity markers transfer the benefits from lower adverse selection to uninformed traders by charging narrower spreads. The findings are in support of **Hypothesis 1** that the ban improved liquidity and eliminated adverse selection on Aquis. Non-banned exchanges saw liquidity measures worsen on average in the after-ban period. Given the tiny 0.4%-1.3% market share of Aquis among displayed trading in the sample period, such notable impacts on liquidity marketwide are unexpected.

Foucault et al. (2017) and Brolley and Cimon (2020) predict that limiting fast liquidity takers eliminates adverse selection and improves liquidity at the costs of competing exchanges which apply no such limitation. Consistent with their predictions, price impact decreased on Aquis and increased on benchmark venues whose level became higher than Aquis' level after the ban. **Appendix A** shows a breakdown comparison against listing exchanges and against the other three MTFs. The pattern that average price impact decreased on Aquis after the ban relative to benchmark venues remains consistent in **Figure A.1a and A.1b**.

Table 3 reports the coefficients in difference-in-difference regressions on liquidity measures. The coefficients of interest are β:s, which test **Hypothesis 1** that the ban improved liquidity and eliminated adverse selection on Aquis. After controlling marketwide liquidity factors, the positive liquidity impacts of banning fast traders on Aquis remain statistically and economically significant.

First, quoted spreads decreased by 3.34 bps compared to non-banned exchanges after the ban. The improvements are equivalent to a 22% drop respectively compared with the pre-event level of Aquis. Second, the ban reduced price impact, which measures adverse selection costs, by more than 20%. The decline is significant for 10-second, 5-minute, and 15-minute intervals. The ban protected liquidity providers from adverse selection and increased their profits, measured by realized spreads, by more than 60%. The improvement in liquidity providing profits supports **Hypothesis 2** that passive liquidity protection makes liquidity provision more profitable and hence more attractive to proprietary traders to supply liquidity. As evidence, liquidity providers at Aquis contributed 9.3% more of EBBO depth, and the time providing EBBO also significantly increased.

4.2 Impacts on proprietary trading

I utilize the Transaction Reporting System (TRS) data to distinguish proprietary trades and their trading sides. The TRS database is managed by the Swedish Financial Supervisory Authority (Finansinspektionen). In accordance with the Markets in Financial Instruments Directive (MiFID), all Swedish and foreign financial institutions must report their transactions on Swedish financial instruments to TRS. The reporting scope of the transaction includes instrument ISIN, date, time, price, volume, side, trading venue, and the trading firm's identification. The data covers transactions on 1) the listing exchange, Nasdaq OMX Stockholm, 2) MTFs outside Sweden including Aquis, BATS, Chi-X, and Turquoise, 3) dark pools, 4) systematic internalizers, and 5) other OTC trading facilities.

I identify proprietary traders as liquidity provider members in the FIA European

Principal Traders Association (FIA EPTA). For each trade on TRS, I locate the nearest quotes before the trade gets executed in RTH intraday order book data. If a sell (buy) trade hits the bid price then the trade is marked as passive (aggressive). Symmetrically, if a buy (sell) trade hits the ask price then the trade is passive (aggressive). The information on aggressive trading by exchanges and trading firms allows me to trace how proprietary traders changed their trading behavior after the ban.

Despite the fact that individual markets are different and the liquidity improvement due to the ban might not be equally shared in each country, the impacts on Swedish blue chip stocks should be representative as Swedish equities are traded at Aquis more than most other European samples. **Table 5** reports the summary statistics for the Swedish equity market, where sample stocks are Nasdaq OMXS30 index components. **Table 5** reports estimation results from the same difference-in-difference model on the Swedish market. I find significant and persistent improvement in profits to the liquidity providers and adverse selection for a 10-second interval in the Swedish sample.

Realized spreads increased by 49% (1.35 bps), and the scale is close to the level in **Table 3**. Adverse selection costs declined by 24% (1.4 bps), more than the European sample. As expected, the ban targets fast latency arbitrage, and impacts are stronger on trading at a higher frequency. The improvement is persistent for a shorter interval (1 second) but vanishes for periods longer than 1 minute[12]. Liquidity provision measured in contribution to EBBO depth and time of quoting at EBBO increased significantly by 10.5% and 9.5% for the Swedish market index. Moreover, the behavior change of proprietary traders was clear as aggressive trading by proprietary traders declined to almost 0 immediately after the ban. For this reason, the Swedish market is worth further investigating to reveal how proprietary trading and fast arbitrage changed at each exchange due to the ban.

In **Figure 4**, it is clear to see a sharp and almost full drop in liquidity taking by

[12] Omitted due to limited space.

proprietary traders (panel *Market*) at Aquis after the ban[13]. HFT liquidity provision (panel *Limit*) remained unchanged. The change on Aquis is consistent with improved liquidity in the DiD regression, which implies that the treated exchange became less exposed to aggressive proprietary trading and less threatened by latency arbitrage after the ban. The total trading volume of all proprietary traders remained stable on other exchanges. The results above illustrate that banning aggressive proprietary trading at one exchange did not intensify aggressive proprietary trading at non-banned exchanges. Still, t-test results in **Table 6** show a slight but significant increase of both liquidity taking and making by Aquis proprietary traders on Turquoise. Meanwhile, they provided much less liquidity on Chi-X and BATS after the ban. However, the share of Aquis in the Swedish market was less than 1% such that any spillover effect was limited on other exchanges.

4.3 Impacts on toxic arbitrage

In this section, I test **Hypothesis 2** by comparing cross-venue toxic arbitrage before and after the ban. Fast traders can implement latency arbitrage either within one exchange or across multiple exchanges. The advantage of cross-exchange latency arbitrage is that the strategy has limited risks exposure in inventory or funding liquidity, and is subject to no short-selling restriction. Moreover, when crossed quotes arise between two exchanges, I can trace both order book messages to identify if any new public information arrives, which exchange fails to update stale quotes, and how long is the latency. Therefore, I focus on cross-exchange latency arbitrage, especially toxic arbitrage, which is accompanied by permanent price shifts. Toxic arbitrage adds to adverse selection even under symmetric information (Foucault et al., 2017). If **Hypothesis 2** holds, it implies that the decrease in adverse selection is achieved by reducing the likelihood of toxic arbitrage trades.

To this aim, I adopt the approach of Foucault et al. (2017) to measure cross-venue

[13] The non-zero HFT liquidity taking is due to matching error when looking up quotes for TRS trades in RTH order book.

arbitrage and toxic arbitrage activities. I consolidate two order books with the bid price from one exchange and the ask from another for each snapshot when quotes change at one of the two exchanges due to a trade or a new quote being posted. Then I mark occurrences in which the bid price at one exchange is higher than the ask price at the other exchange, which is also known as the crossed quotes. The crossed quotes present arbitrage opportunities to buy at a lower ask and sell at a higher bid price simultaneously. For each opportunity, I mark the exchange which is slower in updating quotes leaving the latency arbitrage opportunity as the "stale exchange". I also track how long the opportunity survives at the stale exchange till the opportunity vanishes.

It is worth noting that AQXE, BATE, CHIX, and TRQX are located in the UK while the listing exchange, Nasdaq OMX Stockholm (XSTO), is in Sweden. Therefore, I structure two types of cross-exchange arbitrage opportunities: one only between UK exchanges (such as Aquis-to-BATS) and one only between XSTO and one UK exchange (such as XSTO-to-Aquis). I limit my comparison within each type to control extra delay due to geography distance[14]. However, unlike UK exchanges with milliseconds time stamps, order book message data at XSTO is timestamped only by minutes in the RTH data until August 21st, 2020. The RTH system time, on the contrary, is timestamped by microseconds. The system delay between an actual trade or quote update occurring and the message being recorded in the RTH system is relatively consistent. Therefore, I adjust the delay from RTH system time to proxy the actual exchange time at XSTO. More details are provided in **A.2**.

Taking account of transaction costs to exploit an arbitrage opportunity, I limit the scope of potential opportunities to crossed quotes in which the arbitrage profits, measured as the price difference between the bid and ask prices, is no less than 1 bps of the sum of bid and ask prices. The threshold is different from Foucault et al. (2017) in which they use 0.2 bps of the sum of half quoted spreads at two exchanges. The 1bps threshold comes with reasons. First, the 1 bps threshold represents explicit transaction costs to buy

[14] I am extending this section with European samples, such as Euronext stocks or UK stocks where both the listing exchanges and MTFs are located in the UK without geographic latency.

and sell stock simultaneously at two exchanges. A back-of-the-envelope calculation of the explicit fees rate will be doubling the 0.35-0.5 bps take fees at Nasdaq OMX Stockholm and discount by 35% for OMXS30 index stocks. The estimation is 0.53-0.75 bps[15], which is close to 1 bps. Second, due to the tick size, the minimal price change is at least 1 bps for sample stocks. Therefore, the 1 bps threshold for potential arbitrage profits will not underestimate potential opportunities[16].

According to Foucault et al. (2017), a toxic arbitrage is driven by public information and associated with permanent shifts. On the contrary, a non-toxic arbitrage is driven by liquidity shock and the transient price shift will revert back to the level when the opportunity occurred (as illustrated in **Figure 5**). In this vein, I classify the opportunities into two types: a toxic arbitrage opportunity and a non-toxic opportunity. I mark an arbitrage opportunity as toxic if the price at the fast exchange moves away from the level right before the opportunity arises and is followed by the price at the stale exchange when the opportunity vanishes. Or non-toxic if the price remains unchanged at the fast exchange but reverses at the stale exchange when the opportunity vanishes.

I further decompose the fraction of toxic arbitrage opportunities into two measures: 1) the percentage of toxic arbitrage opportunities from all cross-venue arbitrage opportunities and 2) how likely an arbitrageur successfully exploits a toxic cross-venue arbitrage opportunity with a trade. As illustrated in **Figure 6**, I structure the toxic arbitrage opportunity "mix" measure which is the percentage, φ, of toxic arbitrage opportunities out of total opportunities is the frequency of potential toxic arbitrage race as in (Foucault et al., 2017). The opportunity is terminated either with a new quote or a trade. The another measure relative "speed" of toxic arbitrageur is the probability, π, that a toxic arbitrage opportunity gets terminated with a trade increases with the speed advantage of an arbitrageur over a market maker.

Table 7 tests the change in toxic arbitrage measures for latency arbitrage opportu-

[15]Take fee rates at Cboe Chi-X and BATS Europe is 0.3 bps, which will arrive similar estimation.
[16]The 1bps threshold does not filter out any potential opportunity

nities between any two UK exchanges. The first panel reports that when Aquis Exchange is unable to adjust quotes in time, more than 70% of the cross-exchange latency arbitrage opportunities are due to new information hence toxic. The percentage of toxic arbitrage opportunities remains unchanged after the ban, which is reasonable because restricting latency arbitrage does not restrict new information arriving. The second panel shows that, when Aquis is stale, 41.88% toxic arbitrage opportunities vanish with a trade in which the market maker is sniped. The level is close to the estimation in Foucault et al. (2017) that 48% (112 out of 231) cross-venue arbitrage opportunities ended with toxic trades per day for one set of triangular arbitrage currency pairs. The measure reduced by more than 26% to 15.51% after the ban, which implies liquidity providers saw a higher chance to update stale quotes before being sniped hence facing lower adverse selection risks. The survival time of toxic opportunities contains outliers that push up the average measure and standard deviation. The t-test fails to find any significant changes in the survival time measure. Finally, toxic arbitrage measures at other UK exchanges remain unchanged.

Controlling daily turnover, realized volatility, and fixed effects, I estimate the impacts on toxic arbitrage with a difference-in-difference model similar to the model on liquidity measures. **Table 8** shows consistent results that the fraction of total toxic arbitrage opportunities (φ) and survival time of toxic opportunities remained unchanged but the fraction of toxic arbitrage opportunities picked off by trades significantly declined by 27.86% at Aquis after the ban. In the breakdown analysis, I find that the fraction of toxic arbitrage declined through the "speed" channel and liquidity providers were more likely to avoid sniping and to update stale quotes under toxic arbitrage opportunities. Therefore, liquidity providers subjected to lower adverse selection won higher profits in supplying liquidity and found liquidity providing at Aquis more attractive.

Table 9 and **Table 10** perform the same analysis on toxic arbitrage opportunities between XSTO and UK exchanges, where the UK exchange is stale. The t-test and difference-in-difference regression capture a significant decline in the fraction of toxic arbitrage opportunities terminated by a trade at Aquis. The results support that banning aggressive proprietary traders protects market makers from being sniped and decreases adverse selection costs. It is worth noting that the percentage of toxic arbitrage opportunities that vanished with a trade is below 10% both before and after the ban. The level is way lower than the level of other exchanges as well as the level of Aquis in **Table 7**. One possible reason is that trades at Aquis are less frequent than at the four exchanges without the ban. Meanwhile, quote updates are relatively frequent at Aquis. Therefore, a larger number of toxic arbitrage opportunities in **Table 9** dilutes the fraction of toxic arbitrage trades at Aquis. The decline in the percentage of toxic arbitrage opportunities is shared at all exchanges but insignificant in the difference-in-difference regression. Finally, the survival time for toxic arbitrage opportunities is more concentrated but still remains unchanged.

5 Conclusion and discussion

To conclude, my empirical evidence shows that banning aggressive proprietary trading mitigated adverse selection costs and improves liquidity provision at the exchange. The finding that liquidity improved on the treated exchange is consistent with Foucault et al. (2017), Brolley and Cimon (2020), and Aquilina et al. (2022). Moreover, the ban restrained latency arbitrage especially toxic arbitrage and therefore moderated adverse selection. I find no evidence that banning aggressive proprietary traders on one exchange aggravates aggressive proprietary trading or toxic arbitrage at exchanges without the ban. After the ban, arbitrageurs see fewer opportunities for arbitrage, and liquidity providers have a longer time to update stale quotes at non-banned exchanges, especially exchanges that are most exposed to toxic arbitrage.

However, these results may not be applicable to all situations. First, the treated exchange, Aquis, accounted for only about 2% market share of trading European stocks in 2016. Although the liquidity level was comparable to controlled exchanges like BATS and Turquoise, the minor scale of exchange might be endogenous with illiquidity and problematic latency arbitrage at the first place. Second, banning aggressive proprietary traders is a unique and harsh solution to latency arbitrage. The implementation cuts off substantial trading volume from fast traders. As a consequence, the ban will immediately reduce the revenue of the exchange from the trading volume, which discourages large exchanges to apply.

Banning fast trading firms from liquidity taking is a new design to mitigate latency arbitrage and to protect liquidity. Aquis' ban resembles a speed bump but only on market orders from proprietary traders to address adverse selection. Consistent with the theory of speed bumps, the ban significantly improved the liquidity at Aquis immediately after its implementation. The neutral and weak positive spillover effect on market liquidity outside Aquis deviates from the predictions of Biais et al. (2015) and Brolley and Cimon (2020). One possible explanation for his inconsistency is that the ban leads to fewer fast arbitrage opportunities open to fast arbitrageurs hence reducing latency arbitrage and adverse selection overall. It is also possible that Aquis' market share was too small to affect liquidity on larger venues. Further study on comparable trades submitted by different types of traders to exchanges with and without the ban is therefore suggested to test the alternative explanations.

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Tables

Table 1: Composition of sample stocks

This table lists the 13 European market indices, the listing exchanges, and the numbers of constituent stocks in the sample.

Major market index	Exchange	#Sample stocks
AEX 25	Amsterdam	20
BEL 20	Brussels	7
KFX 20	Copenhagen	7
DAX 30	Frankfurt	17
IBEX 35	Madrid	12
HSE 25	Helsinki	7
FTSE 100	London	41
FTSE/MIB 40	Milan	17
OBX 25	Oslo	8
CAC 40	Paris	37
OMXS30	Stockholm	20
PSI 20	Lisbon	1
SMI 20	Zurich	2
Total	341 constituents	200

Note: the FTSE/MIB 40 Index consisted of 41 constituents in the sample period.

Table 2: Summary statistics of liquidity, European sample

This table reports liquidity measures for Aquis, MTFs, and listing exchanges. *Quoted spread* measures the distance between bid and ask quotes relative to the midpoint bid and ask quotes. *Effective spread* is the relative difference between trade price and the midpoint. *Realized spread* is the relative difference between trade price and the midpoint in 10 seconds, 1 minute, and 5 minutes respectively. *Price impact* is the relative change of midpoint in 10 seconds, 1 minute, and 5 minutes respectively. *% of EBBO depth* and *Seconds at EBBO* measures the share of total depth and the total seconds when the exchange contributes to either side of the EBBO. Intraday observations are winsorized to 5% and 95% by stocks, days, and exchanges. All spreads and price impact are for a round-trip trade and in basis points. All measures are aggregate at the stock-day-exchange level.

	Panel A: Aquis					
	Pre-event			Post-event		
	Mean	Std.Dev.	Median	Mean	Std.Dev.	Median
Quoted spread	15.42	13.76	11.52	13.69	12.91	9.37
Effective spread	7.76	4.98	6.66	7.98	5.10	6.87
Realized spread 10Sec	2.13	6.10	2.03	3.20	6.25	2.71
Realized spread 1Min	2.05	9.05	2.11	3.19	9.28	2.68
Realized spread 5Min	1.79	17.03	2.00	3.13	17.60	2.54
Price impact 10Sec	5.61	7.69	3.95	4.77	7.28	3.31
Price impact 1Min	5.71	10.34	4.21	4.80	9.86	3.59
Price impact 5Min	5.97	17.57	4.61	4.85	17.63	3.83
% of EBBO depth	7.55	5.73	6.79	15.65	8.29	16.49
Seconds at EBBO	1083.59	3282.81	199.19	1971.98	4987.39	540.14
Turnover (mShares)	13.29	42.64	0.94	18.41	45.17	1.45
Realized volatility	18.75	10.47	16.16	19.95	12.44	16.69
Observations		6255			6020	

	Panel B: MTFs					
	Pre-event			Post-event		
	Mean	Std.Dev.	Median	Mean	Std.Dev.	Median
Quoted spread	11.06	10.32	8.87	12.38	15.05	9.05
Effective spread	6.33	4.20	5.46	6.57	4.17	5.65
Realized spread 10Sec	0.31	2.93	-0.24	0.28	2.75	-0.18
Realized spread 1Min	0.29	3.30	-0.10	0.18	3.58	-0.12
Realized spread 5Min	0.28	5.16	0.08	0.37	5.45	0.21
Price impact 10Sec	6.01	4.31	4.91	6.29	4.56	5.04
Price impact 1Min	6.05	4.94	4.82	6.40	5.47	5.00
Price impact 5Min	6.06	6.26	4.83	6.21	6.81	4.83
% of EBBO depth	15.39	10.33	13.02	13.51	9.03	11.64
Seconds at EBBO	1337.64	2869.68	444.32	1069.51	1988.11	407.36
Turnover (mShares)	293.83	751.36	19.85	290.28	717.35	18.52
Realized volatility	18.81	10.53	16.24	20.06	12.51	16.81
Observations		19311			18480	

Table 2: Summary statistics of liquidity, European sample (Continued)

This table reports liquidity measures for Aquis, MTFs, and listing exchanges. *Quoted spread* measures the distance between bid and ask quotes relative to the midpoint bid and ask quotes. *Effective spread* is the relative difference between the trade price and the midpoint. *Realized spread* is the relative difference between the trade price and the midpoint in 10 seconds, 1 minute, and 5 minutes respectively. *Price impact* is the relative change of midpoint in 10 seconds, 1 minute, and 5 minutes respectively. *% of EBBO depth* and *Seconds at EBBO* measures the share of total depth and the total seconds when the exchange contributes to either side of the EBBO. Intraday observations are winsorized to 5% and 95% by stocks, days, and exchanges. All spreads and price impact are for a round-trip trade and in basis points. All measures are aggregate at the stock-day-exchange level.

	Panel C: Listing exchanges					
	Pre-event			Post-event		
	Mean	Std.Dev.	Median	Mean	Std.Dev.	Median
Quoted spread	6.43	58.38	6.89	8.22	6.34	7.09
Effective spread	13.85	24.06	5.79	13.99	25.98	5.79
Realized spread 10Sec	8.21	25.08	0.15	7.94	27.10	0.08
Realized spread 1Min	7.82	25.20	0.26	7.58	27.26	0.17
Realized spread 5Min	7.73	25.57	0.42	7.84	27.43	0.57
Price impact 10Sec	5.53	4.92	4.43	5.99	5.55	4.55
Price impact 1Min	6.03	5.45	4.39	6.45	5.93	4.71
Price impact 5Min	6.22	6.38	4.70	6.25	6.41	4.78
% of EBBO depth	42.33	13.60	40.43	39.83	14.07	36.83
Seconds at EBBO	4487.06	11001.90	1419.79	4307.17	9899.81	1349.51
Turnover (mShares)	76.00	99.77	43.62	73.94	98.93	42.63
Realized volatility	18.81	10.53	16.24	20.06	12.51	16.81
Observations		6437			6160	

Table 3: Difference-in-difference on liquidity, European sample

This table presents the estimators from the difference-in difference regression model in **Equation 1**:

$$y_{i,t,m} = \alpha_i + \beta_t + \gamma_m + \delta Treatment_m \times Post_t + \lambda X_{i,t} + \varepsilon_{i,t,m} \quad (1)$$

where $y_{i,t,m}$ denotes liquidity measure for stock i on day t and exchange m. The treatment dummy $Treatment_m$ equals to 1 if exchange m is the Aquis Exchange, or 0 if m is one of the MTFs or listing exchanges. The event dummy $Post_t$ equals to 1 for date t within February 8 to March 4, 2016. Stock-day level control variables $X_{i,t}$ include total turnover of stock i on date t from all exchanges in logarithm form, and daily average realized volatility of EBBO midprice in 5-minute intervals in basis points. Finally, I control fixed effects of stock, date, and exchanges. t-statistics based on standard errors clustered by stock and date are reported in parentheses.

	Quoted spread (1)	Effective spread (2)	Realized spread 10 Sec (3)	Realized spread 1 Min (4)	Realized spread 5 Min (5)	Price impact 10 Sec (6)	Price impact 1 Min (7)	Price impact 5 Min (8)	EBBO depth % (9)	EBBO depth time (10)
Treat.×Post	-3.34	0.10	0.97	1.32	1.35	-0.87	-1.21	-1.23	9.33	1165.38
	(-3.70)	(0.51)	(3.43)	(4.10)	(2.43)	(-4.43)	(-4.27)	(-2.42)	(11.16)	(4.82)
Turnover	1.76	-0.60	-0.16	0.04	-0.62	-0.43	-0.59	0.07	0.04	206.92
	(0.69)	(-1.54)	(-0.54)	(0.13)	(-1.19)	(-1.22)	(-1.23)	(0.16)	(0.45)	(1.51)
Volatility	-0.14	0.12	-0.01	-0.06	-0.03	0.14	0.18	0.15	0.00	-35.06
	(-0.65)	(3.43)	(-0.76)	(-3.12)	(-0.82)	(4.24)	(3.78)	(3.64)	(-0.82)	(-3.82)
Stock FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Date FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Venue FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
# obs.	38948	38948	38945	38942	38941	38945	38942	38941	38948	38948
R^2	0.10	0.80	0.78	0.72	0.53	0.58	0.43	0.18	0.76	0.63

Table 4: Summary statistics of liquidity, Swedish sample

This table reports liquidity measures for Aquis, MTFs, and listing exchanges. *Quoted spread* measures the distance between bid and ask quotes relative to the midpoint bid and ask quotes. *Effective spread* is the relative difference between the trade price and the midpoint. *Realized spread* is the relative difference between the trade price and the midpoint in 1 second, 10 seconds, and 1 minute respectively. *Price impact* is the relative change of midpoint in 1 second, 10 seconds, and 1 minute respectively. *% of EBBO depth* and *Seconds at EBBO* measures the share of total depth and the total seconds when the exchange contributes to either side of the EBBO. Intraday observations are winsorized to 5% and 95% by stocks, days, and exchanges. All spreads and price impact are for a round-trip trade and in basis points. All measures are aggregate at the stock-day-exchange level.

	Panel A: Aquis					
	Pre-event			Post-event		
	Mean	Std.Dev.	Median	Mean	Std.Dev.	Median
Quoted spread	13.09	5.22	12.11	12.44	4.85	11.48
Effective spread	8.60	4.66	7.85	8.30	4.43	7.51
Realized spread 1Sec	3.43	4.07	3.53	4.39	4.64	4.27
Realized spread 10Sec	2.75	5.75	3.18	3.98	5.55	3.72
Realized spread 1Min	2.71	6.16	3.07	3.57	8.49	3.69
Price impact 1Sec	5.17	5.59	3.61	3.92	5.62	2.91
Price impact 10Sec	5.85	7.39	4.22	4.33	6.96	3.58
Price impact 1Min	5.89	7.67	4.20	4.74	9.99	3.65
% of EBBO depth	40.76	15.24	40.53	49.51	16.00	48.72
Seconds at EBBO	10.60	4.24	11.21	18.93	3.82	19.21
Turnover (mShares)	14.84	1.73	15.10	14.93	1.71	15.26
Realized volatility	19.29	7.32	17.31	18.40	7.94	16.09
Observations		553			548	
	Panel B: MTFs					
	Pre-event			Post-event		
	Mean	Std.Dev.	Median	Mean	Std.Dev.	Median
Quoted spread	13.30	11.16	10.98	19.55	40.03	11.04
Effective spread	6.90	4.54	5.67	6.60	3.54	5.77
Realized spread 1Sec	0.55	2.80	-0.05	0.43	3.88	0.01
Realized spread 10Sec	-0.30	2.27	-0.48	-0.37	3.81	-0.59
Realized spread 1Min	-0.26	2.33	-0.38	-0.33	3.86	-0.51
Price impact 1Sec	6.38	2.96	5.70	6.20	4.04	5.76
Price impact 10Sec	7.24	4.12	6.12	7.00	4.51	6.32
Price impact 1Min	7.19	4.35	5.99	6.96	4.58	6.28
% of EBBO depth	56.76	23.81	62.28	54.64	23.15	59.06
Seconds at EBBO	14.27	7.23	13.39	12.85	6.53	12.41
Turnover (mShares)	17.59	1.29	17.72	17.57	1.34	17.79
Realized volatility	20.22	9.68	17.35	19.13	11.59	16.08
Observations		1800			1800	

Table 4: Summary statistics of liquidity, Swedish sample (Continued)

This table reports liquidity measures for Aquis, MTFs, and listing exchanges. *Quoted spread* measures the distance between bid and ask quotes relative to the midpoint bid and ask quotes. *Effective spread* is the relative difference between the trade price and the midpoint. *Realized spread* is the relative difference between the trade price and the midpoint in 1 second, 10 seconds, and 1 minute respectively. *Price impact* is the relative change of midpoint in 1 second, 10 seconds, and 1 minute respectively. *% of EBBO depth* and *Seconds at EBBO* measures the share of total depth and the total seconds when the exchange contributes to either side of the EBBO. Intraday observations are winsorized to 5% and 95% by stocks, days, and exchanges. All spreads and price impact are for a round-trip trade and in basis points. All measures are aggregate at the stock-day-exchange level.

	Panel C: Listing exchanges					
	Pre-event			Post-event		
	Mean	Std.Dev.	Median	Mean	Std.Dev.	Median
Quoted spread	9.68	3.66	8.97	9.83	3.62	9.08
Effective spread	5.37	3.15	4.57	5.04	3.12	4.26
Realized spread 1Sec	0.41	2.26	-0.03	0.29	2.51	-0.14
Realized spread 10Sec	-0.06	2.33	-0.22	-0.37	2.11	-0.52
Realized spread 1Min	0.10	2.64	-0.07	-0.29	2.20	-0.36
Price impact 1Sec	4.96	2.09	4.58	4.77	1.74	4.48
Price impact 10Sec	5.67	3.20	4.76	5.55	2.83	4.93
Price impact 1Min	5.69	3.65	4.71	5.56	3.20	4.70
% of EBBO depth	84.02	7.46	85.53	82.47	8.15	83.50
Seconds at EBBO	47.35	12.81	43.94	44.05	11.78	40.84
Turnover (mShares)	19.35	0.75	19.36	19.31	0.72	19.36
Realized volatility	20.22	9.69	17.35	19.13	11.60	16.08
Observations		600			600	

Table 5: Difference-in-difference on liquidity, Swedish sample

This table presents the difference-in-difference estimators based on the subsample of Nasdaq OMXS30 index components. The model defined in **Equation 1** is the same as in **Table 3**:

$$y_{i,t,m} = \alpha_i + \beta_t + \gamma_m + \delta Treatment_m \times Post_t + \lambda X_{i,t} + \varepsilon_{i,t,m} \quad (1)$$

where $y_{i,t,m}$ denotes liquidity measure for stock i on day t and exchange m. The treatment dummy $Treatment_m$ equals to 1 if exchange m is the Aquis Exchange, or 0 if m is one of the MTFs or listing exchanges. The event dummy $Post_t$ equals 1 for date t from February 8 to March 4, 2016. Stock-day level control variables $X_{i,t}$ include total turnover of stock i on date t from all exchanges in logarithm form, and daily average realized volatility of EBBO midprice in 5-minute intervals in basis points. Finally, I control fixed effects of stock, date, and exchanges. t-statistics based on standard errors clustered by stock and date are reported in parentheses.

	Quoted spread (1)	Effective spread (2)	Realized spread 1 Sec (3)	Realized spread 10 Sec (4)	Realized spread 1 Min (5)	Price impact 1 Sec (6)	Price impact 10 Sec (7)	Price impact 1 Min (8)	EBBO quotes % (9)	EBBO depth % (10)
Treat.×Post	-4.67	-0.10	0.98	1.35	1.04	-1.09	-1.41	-1.09	10.35	9.45
	(-1.25)	(-0.35)	(2.61)	(3.58)	(2.70)	(-2.34)	(-2.96)	(-1.90)	(4.86)	(9.30)
Ln(Turnover)	-7.71	-0.17	0.12	-0.08	-0.17	-0.28	-0.09	-0.005	7.14	4.98
	(-1.55)	(-1.72)	(0.54)	(-0.50)	(-1.28)	(-1.49)	(-0.61)	(-0.03)	(7.58)	(5.50)
Volatility	0.28	0.09	0.02	-0.02	-0.02	0.06	0.11	0.11	-0.18	-0.09
	(2.84)	(7.77)	(0.91)	(-0.67)	(-0.54)	(3.73)	(5.06)	(3.51)	(-1.78)	(-3.08)
Stock FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Date FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Exchange FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
# obs.	5899	5899	5899	5899	5899	5899	5899	5899	5899	5899
R^2	0.53	0.75	0.36	0.23	0.14	0.37	0.44	0.40	0.78	0.85

Table 6: Trading of affected HFT traders

This table compares the trading behavior of affected HFTs before and after the ban across exchanges. The measure *Presence* is the relative trading volume of HFTs to the total trading volume within each exchange. *Limit* (*Market*) is the relative limit (market) order volume from HFTs to the total limit (market) order volume.

Activity	Before	After	Difference	t-stat	p-value
% in total trading volume					
XSTO	21.25	22.08	0.84	1.81	0.07
CHIX	24.70	22.28	-2.42	-5.93	0.00
BATE	28.50	23.65	-4.85	-8.23	0.00
TRQX	37.23	38.29	1.06	2.17	0.03
AQXE	54.55	48.70	-5.85	-11.27	0.00
% in total liquidity taking					
XSTO	25.39	25.72	0.33	0.74	0.46
CHIX	31.75	31.56	-0.19	-0.40	0.69
BATE	34.13	34.97	0.83	1.32	0.19
TRQX	42.61	44.04	1.44	2.71	0.01
AQXE	18.47	1.30	-17.17	-14.19	0.00
% in total liquidity making					
XSTO	19.18	20.06	0.88	1.53	0.13
CHIX	17.27	12.21	-5.06	-8.38	0.00
BATE	22.49	13.72	-8.77	-8.88	0.00
TRQX	44.09	45.69	1.60	1.82	0.07
AQXE	92.68	97.80	5.12	6.23	0.00

Table 7: Level changes in cross-venue arbitrage between UK exchanges

This table compares cross-venue toxic arbitrage opportunities before and after the ban. Cross-venue arbitrage opportunities are crossed quotes occurrences in which the price difference is at least 1 bps of the sum of crossed bid and ask prices. If the price level reverses to the level before the opportunity arises, then the opportunity is identified as non-toxic. Otherwise, if the price shifts permanently, the opportunity is toxic.

According to Foucault et al. (2017), the number of toxic arbitrage opportunities out of total opportunities is the frequency of potential toxic arbitrage race (the “mix” measure φ). The probability that a toxic arbitrage opportunity gets terminated with a trade measures for the speed advantage of an arbitrageur over a market maker(the “speed” measure π). For a toxic arbitrage opportunity, the survival time is measured from the opportunity arising to vanishing at the stale exchange. The table reports the three measures by exchanges that are slower in updating quotes during the arbitrage opportunity. Due to geography latency between XSTO and UK exchange, reported cross-venue arbitrage opportunities are limited to MTF-to-MTF exchange pairs.

	Before	After	After-Before	t-val	p-val
% toxic oppo. in all oppo.					
AQXE	79.17	72.52	-6.65	-1.13	0.26
BATE	63.79	47.66	-16.13	-2.72	0.01
CHIX	42.80	44.84	2.04	0.44	0.66
TRQX	61.29	59.24	-2.05	-0.41	0.68
% toxic trades in toxic oppo.					
AQXE	41.88	15.51	-26.38	-4.03	0.00
BATE	64.71	70.56	5.86	0.81	0.42
CHIX	87.48	87.54	0.06	0.02	0.99
TRQX	85.38	85.55	0.18	0.04	0.97
Survival time (milliseconds)					
AQXE	10.20	12.15	1.95	0.14	0.89
BATE	0.90	12.52	11.61	1.83	0.07
CHIX	2.44	15.18	12.74	1.45	0.15
TRQX	23.07	2.97	-20.10	-1.53	0.13

Table 8: Toxic arbitrage between UK exchanges

This table presents difference-in-difference regression on toxic arbitrage measures. The model is:

$$y_{i,t,m} = \alpha_i + \beta Treatment_m + \gamma Post_t + \delta Treatment_m \times Post_t + \lambda X_{i,t} + \varepsilon_{i,t,m} \quad (3)$$

According to Foucault et al. (2017), the number of toxic arbitrage opportunities out of total opportunities is the frequency of potential toxic arbitrage race (the "mix" measure φ). The probability that a toxic arbitrage opportunity gets terminated with a trade measures for the speed advantage of an arbitrageur over a market maker(the "speed" measure π). For a toxic arbitrage opportunity, the survival time is measured from the opportunity arising to vanishing at the stale exchange. Due to geography latency between XSTO and UK exchange, reported cross-venue arbitrage opportunities are limited to MTF-to-MTF exchange pairs. Fixed effects are controlled for stocks. t-statistics based on standard errors clustered by stock and date are reported in parentheses.

	% toxic oppo. in all oppo.	% toxic trades in toxic oppo.	Survival time
Treatment×Post	-3.01	-27.86	-0.55
	(-0.50)	(-2.72)	(-0.04)
Ln(Turnover)	-1.32	1.46	-12.17
	(-1.09)	(0.80)	(-1.84)
Realized volatility (bps)	0.36	0.08	-0.55
	(1.53)	(0.42)	(-1.10)
Stock FE	Yes	Yes	Yes
Date FE	Yes	Yes	Yes
Exchange FE	Yes	Yes	Yes
# obs.	1041	720	722
R^2	0.09	0.32	0.02

Table 9: Level changes in cross-venue arbitrage between XSTO and UK exchanges

This table compares cross-venue toxic arbitrage opportunities before and after the ban. Cross-venue arbitrage opportunities are crossed quotes occurrences in which the price difference is at least 1 bps of the sum of crossed bid and ask prices. If the price level reverses to the level before the opportunity arises, then the opportunity is identified as non-toxic. Otherwise, if the price shifts permanently, the opportunity is toxic.

According to Foucault et al. (2017), the number of toxic arbitrage opportunities out of total opportunities is the frequency of potential toxic arbitrage race (the "mix" measure φ). The probability that a toxic arbitrage opportunity gets terminated with a trade measures for the speed advantage of an arbitrageur over a market maker(the "speed" measure π). For a toxic arbitrage opportunity, the survival time is measured from the opportunity arising to vanishing at the stale exchange. Due to geography latency between XSTO and UK exchange, reported cross-venue arbitrage opportunities are limited to XSTO-to-MTF exchange pairs where the UK MTF is stale.

	Before	After	After-Before	t-val	p-val
% toxic oppo. in all oppo.					
AQXE	47.31	38.55	-8.75	-3.65	0.00
BATE	41.52	31.00	-10.51	-4.79	0.00
CHIX	38.97	31.62	-7.36	-3.95	0.00
TRQX	31.92	26.42	-5.51	-3.20	0.00
% toxic trades in toxic oppo.					
AQXE	5.23	2.74	-2.49	-2.14	0.03
BATE	72.52	74.78	2.26	0.80	0.42
CHIX	91.88	92.79	0.92	0.70	0.48
TRQX	81.10	83.86	2.76	1.34	0.18
Survival time (milliseconds)					
AQXE	26.00	30.42	4.42	0.72	0.47
BATE	28.49	27.01	-1.49	-0.26	0.80
CHIX	28.02	26.38	-1.65	-0.42	0.68
TRQX	33.89	29.30	-4.60	-0.76	0.45

Table 10: Toxic arbitrage between XSTO and UK exchanges

This table presents difference-in-difference regression on toxic arbitrage measures. The model is:

$$y_{i,t,m} = \alpha_i + \beta Treatment_m + \gamma Post_t + \delta Treatment_m \times Post_t + \lambda X_{i,t} + \varepsilon_{i,t,m} \quad (5)$$

According to Foucault et al. (2017), the number of toxic arbitrage opportunities out of total opportunities is the frequency of potential toxic arbitrage race (the "mix" measure φ). The probability that a toxic arbitrage opportunity gets terminated with a trade measures for the speed advantage of an arbitrageur over a market maker(the "speed" measure π). For a toxic arbitrage opportunity, the survival time is measured from the opportunity arising to vanishing at the stale exchange. Due to geography latency between XSTO and UK exchange, reported cross-venue arbitrage opportunities are limited to XSTO-to-MTF exchange pairs where the UK MTF is stale. Fixed effects are controlled for stocks. t-statistics based on standard errors clustered by stock and date are reported in parentheses.

	% toxic oppo. in all oppo.	% toxic trades in toxic oppo.	Survival time
Treatment×Post	-0.74	-4.21	5.33
	(-0.37)	(-2.35)	(0.91)
Ln(Turnover)	-0.50	-1.19	-2.19
	(-0.55)	(-2.37)	(-0.95)
Realized volatility (bps)	0.23	-0.08	-0.29
	(1.39)	(-1.06)	(-0.59)
Stock FE	Yes	Yes	Yes
Date FE	Yes	Yes	Yes
Exchange FE	Yes	Yes	Yes
# obs.	3812	2907	2907
R^2	0.20	0.68	0.08

Figures

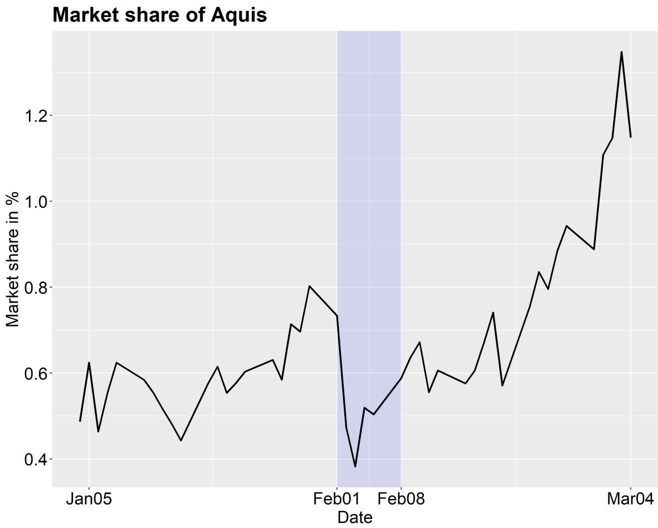


Figure 1: Market share of Aquis

The plot shows the growth of Aquis Exchange over time one month before and after the trading ban took effect on February 8th, 2016. Market share data are aggregated from all displayed trading in 13 markets, which are London, Paris, Frankfurt, Zurich, Amsterdam, Madrid, Milan, Oslo, Helsinki, Lisbon, Brussels, Copenhagen, and Stockholm. Data is sourced from Cboe European Equities Market Share (https://markets.cboe.com/europe/equities/market_share/market/).

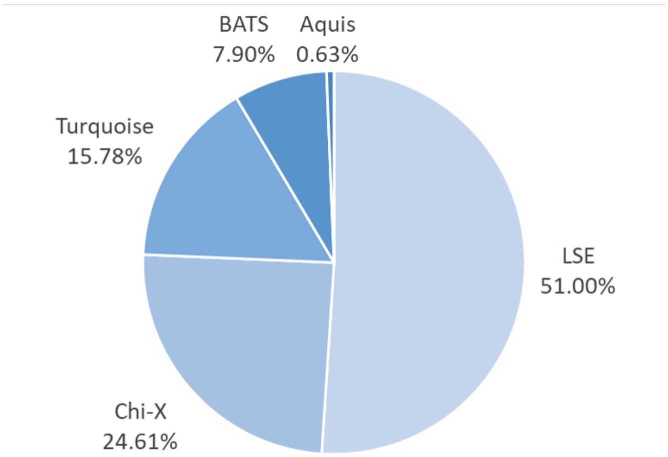


Figure 2: Market share among displayed trading exchanges

The pie chart presents the monthly average market share in displayed trading volume among London Stock Exchange (LSE), Chi-X, BATS, Turquoise, and Aquis in January 2016. The sample consists of stocks listed on LSE. Data is sourced from Cboe European Equities Market Share (https://markets.cboe.com/europe/equities/market_share/market/).

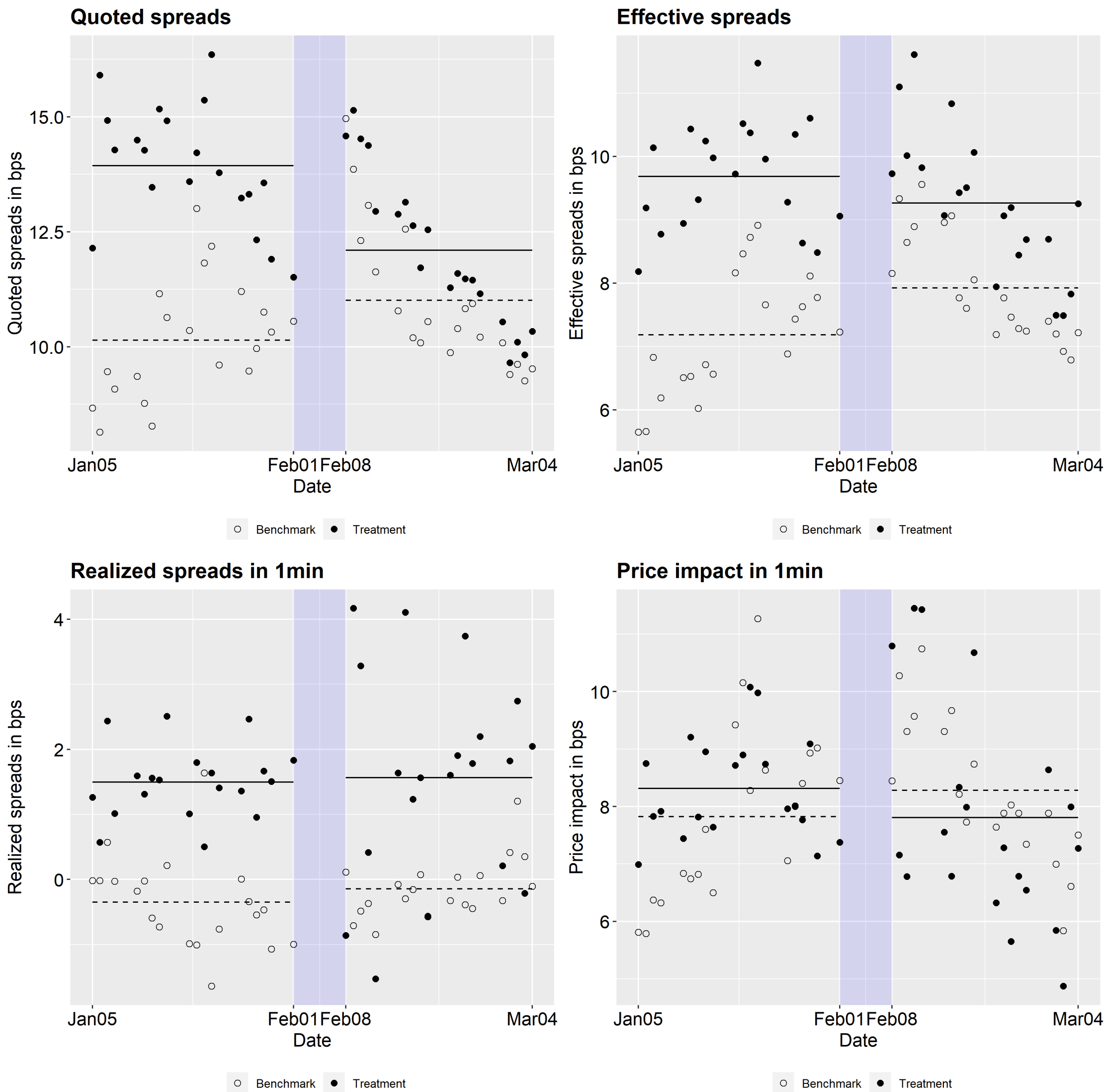


Figure 3: Graphical illustration of the impact on liquidity

This figure compares changes in liquidity measures on Aquis and the benchmark venues (both the listing exchanges and MTFs other than Aquis) before and after the membership ban. For each measure, I plot the average across 200 sample stocks for the treated venue, Aquis (solid fill), and the controlled venues (outline only). The level lines indicate the time-serial averages before and after the ban for the treated (solid) and the controlled (dashed) venues.

Figure 4: Proprietary trading across venues

This figure compares proprietary trading behavior on five exchanges one month before and after Aquis' ban. The percent share of trading volume is aggregated by order types among proprietary traders. The top panel shows the percentage of proprietary trading in total trading volume. The middle panel shows the percentage of liquidity provided by proprietary traders. The last panel shows the percentage of liquidity taken by proprietary traders. The sample instruments are Nasdaq OMX Stockholm 30 Index constituent stocks.

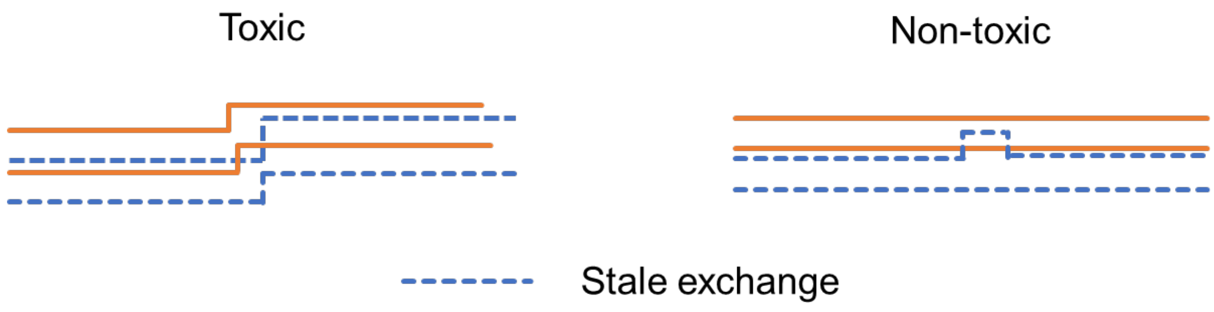


Figure 5: Toxic vs. non-toxic arbitrage opportunities

The two made-up examples illustrate how a toxic or non-toxic arbitrage opportunity arises and vanishes cross-exchange. The orange solid lines represent the bid and ask quotes at the "fast" exchange and the blue dashed lines represent the "stale" exchange. If new public information arrives on both exchanges, quotes at the "fast" exchange will jump first. The "stale" exchange is unable to update quotes simultaneously and creates an arbitrage opportunity to buy low at the "stale" exchange and sell high at the "fast". The opportunity vanishes when quotes at the "stale" exchange also jump, which can be due to new quotes or a trade. The opportunity is driven by information and vanishes with permanent price movement. According to Foucault et al. (2017), I categorize such opportunities as toxic. On the contrary, an opportunity that is driven by liquidity shock and vanishes with price reverse will be categorized as non-toxic.

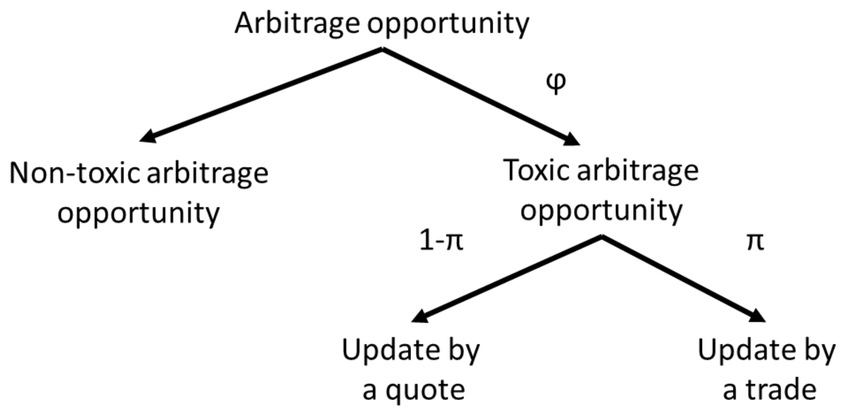


Figure 6: Breakdown of toxic arbitrage measures

This figure breaks down the measures for toxic arbitrage in Foucault et al. (2017). Among the total identified arbitrage opportunities, φ of the opportunities company permanent price move and marked as toxic. φ measures the percentage of toxic arbitrage opportunity arbitrageurs can exploit. A higher φ implies more often a market maker is subject to adverse selection. Among those toxic arbitrage opportunities, π of the opportunities are adjusted by trades while $1 - \pi$ by quotes update. π measures the likelihood that an arbitrageur successfully snipes stale quotes. A higher π implies a higher chance in which a market maker is adversely selected.

Appendix A. Graphical comparison in subgroups

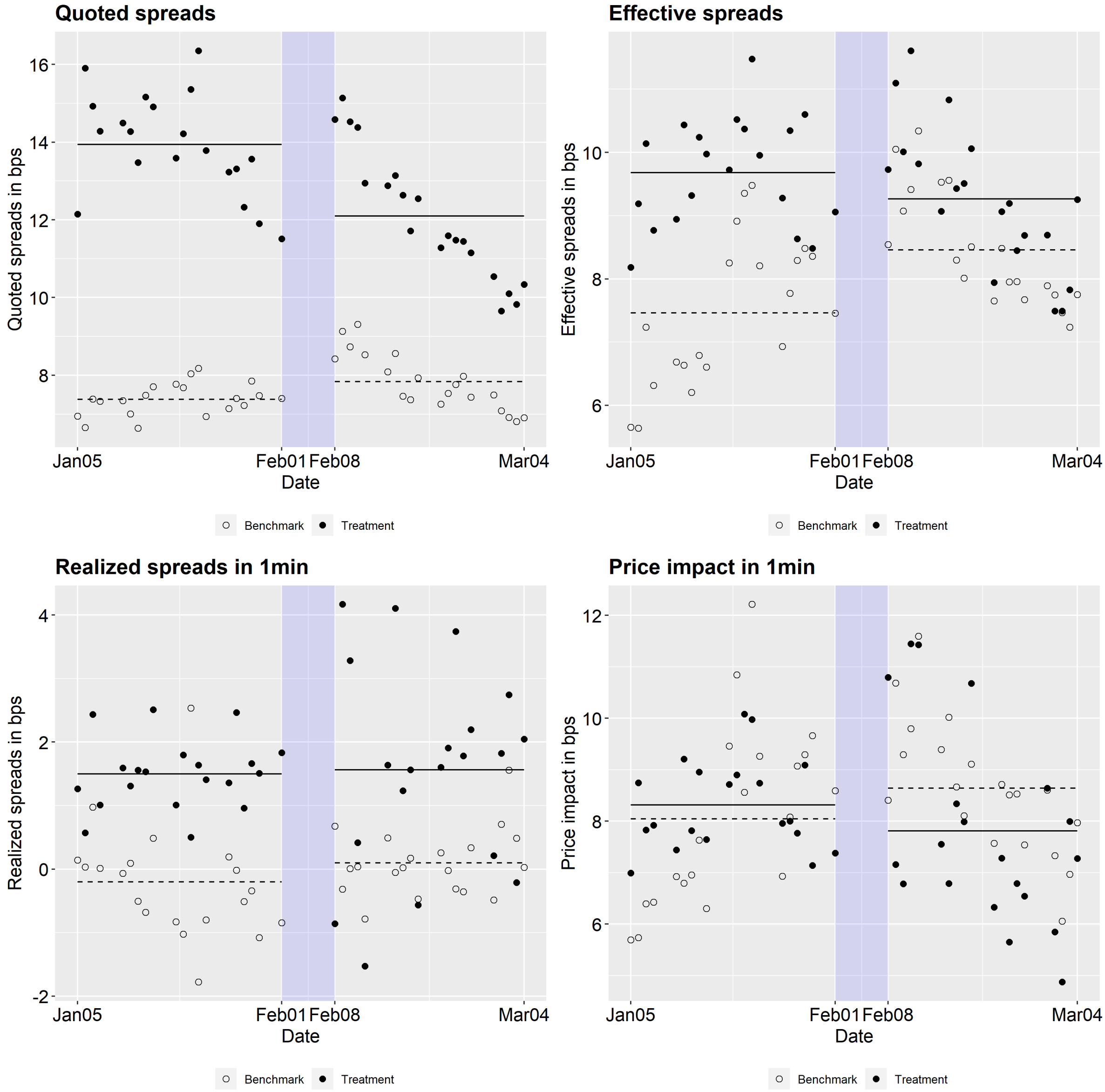


Figure A.1a: Graphical comparison benchmark on the listing exchanges

This figure compares changes in liquidity measures on Aquis and the listing exchanges before and after the membership ban. For each measure, I plot the average across 200 sample stocks for the treated venue, Aquis (solid fill), and the controlled venues (outline only). The level lines indicate the time-serial averages before and after the ban for the treated (solid) and the controlled (dashed) venues.

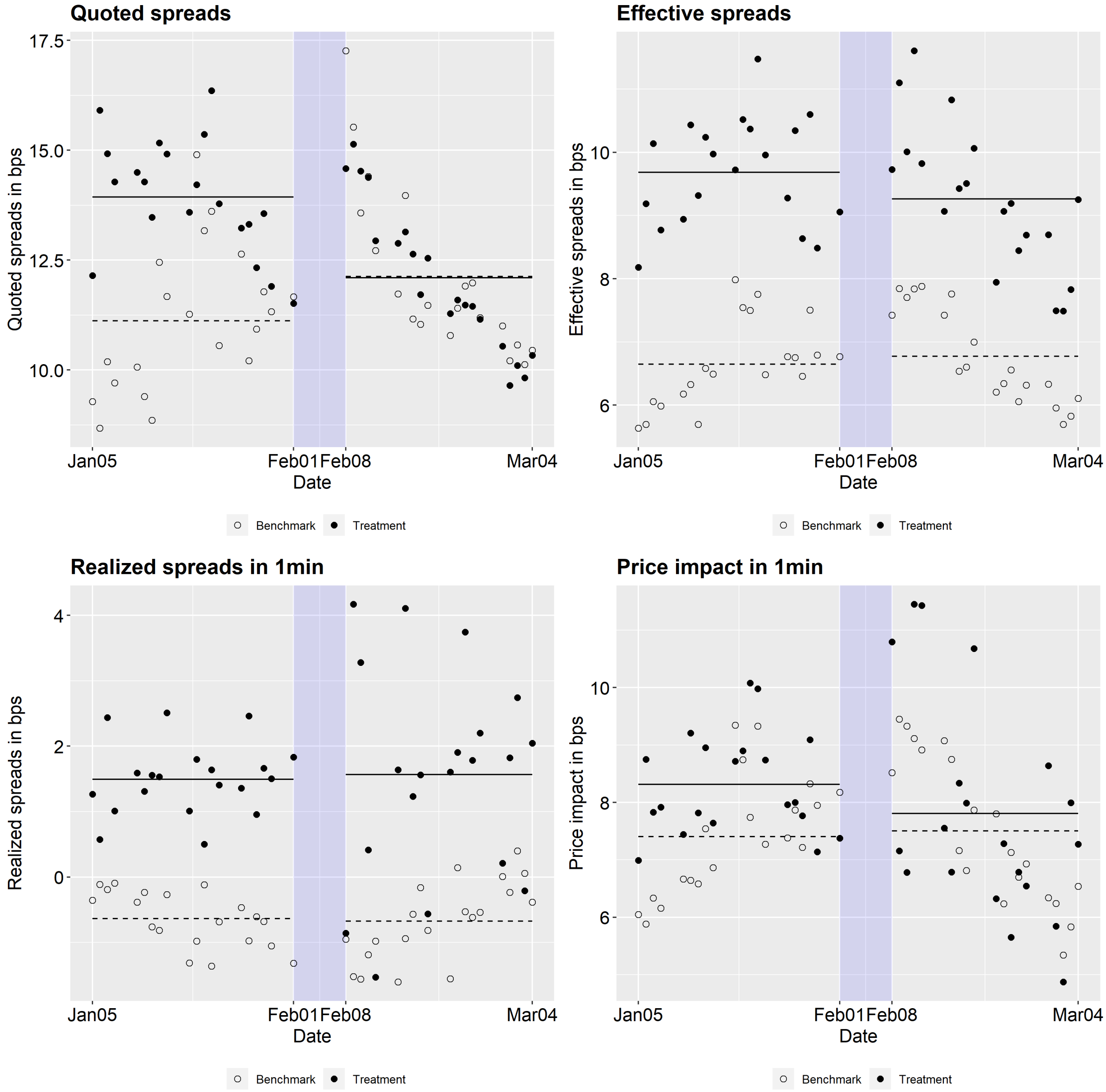
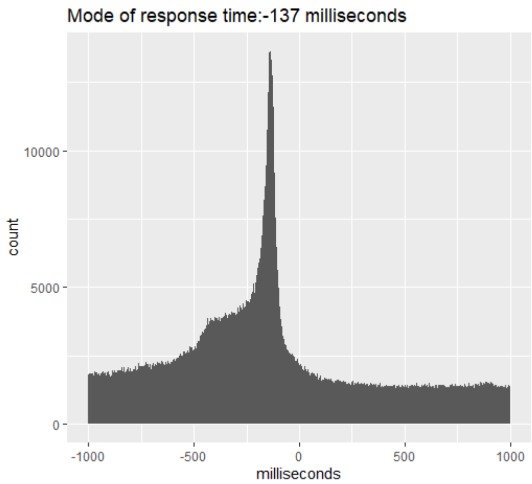
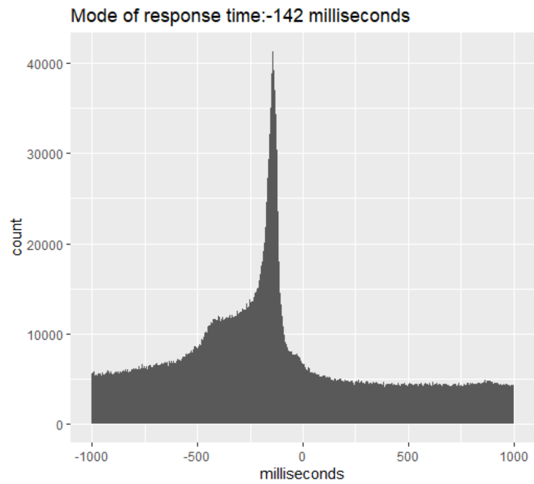


Figure A.1b: Graphical comparison benchmark on other MTFs

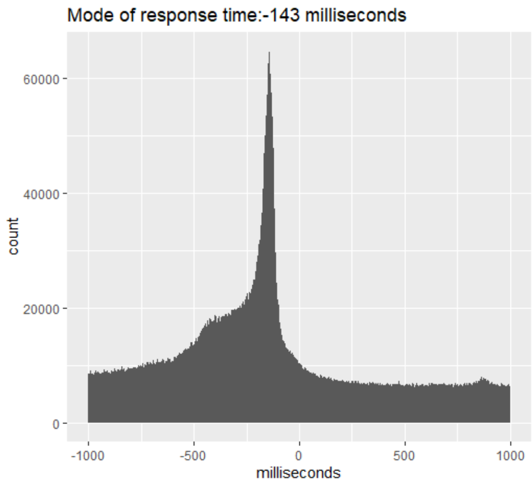
This figure compares changes in liquidity measures on Aquis and MTFs other than Aquis before and after the membership ban. For each measure, I plot the average across 200 sample stocks for the treated venue, Aquis (solid fill), and the controlled venues (outline only). The level lines indicate the daily averages before and after the ban for the treated (solid) and the controlled (dashed) venues.



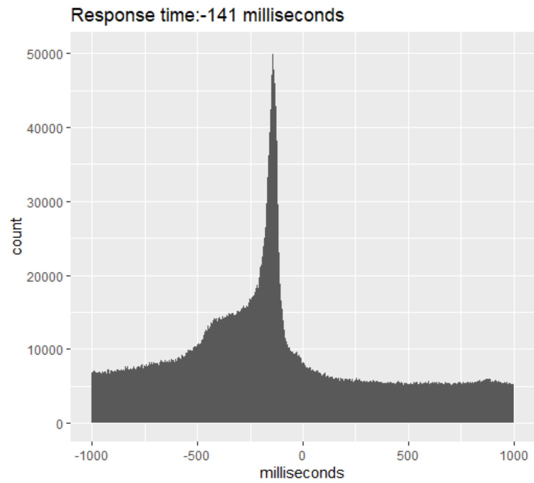
(a) Aquis



(b) BATS



(c) Chi-X



(d) Turquoise

Figure A.2: Response time between Nasdaq OMX and UK exchanges

The histograms present the distribution of response time between a signal (a trade) occurring at Nasdaq OMX Stockholm (XSTO) and a quote update at a UK exchange around the signal. The response time is measured as the RTH system time at XSTO with geographic and system delay and the exact exchange time at UK exchanges. The mode value of response time is located between -143 to -137 milliseconds. Based on the distribution, I assume the RTH system time is delayed for about 150 milliseconds and turns the clock at XSTO backward by 150 milliseconds.