Hope at a Reasonable Price: Customer Use of Limit Orders in the 0DTE Market*

Lei Fu
Purdue University and U.S. Securities and Exchange Commission

Su Li
U.S. Securities and Exchange Commission

David K. Musto
Wharton School, University of Pennsylvania

Neil D. Pearson
University of Illinois at Urbana-Champaign and CDI Research Fellow

March 16, 2025

Abstract

Wide quoted spreads and the explosion of 0DTE option trading suggest possible exploitation of customers. In contrast, we find that customers' costs of trading with NMLOs are low. We first identify and correct a sequencing issue in the OPRA trade and quote data that puts the quote that *followed* a trade *before* it and then use quote condition codes to identify customer NMLOs. For the actively traded slightly OTM options, customers are at the BBO more than half the time in recent data. A large fraction of volume is due to customer NMLOs, which execute at low cost.

JEL codes: G12, G13, G23

Keywords: 0DTE options, options trading, OPRA, non-marketable limit orders

---

* This paper is part of the Division of Economic and Risk Analysis' (DERA's) Working Paper Series. Papers in this series investigate a broad range of issues relevant to the Commission's mission and are preliminary materials disseminated to stimulate discussion and critical comment. Inclusion of a paper in this series does not indicate a Commission determination to take any particular action. References to this paper, and all papers in the DERA Working Paper Series, should indicate that the paper is a "DERA Working Paper." The Securities and Exchange Commission disclaims responsibility for any private publication or statement of any SEC employee or Commissioner. This paper expresses the authors' views and does not necessarily reflect those of the Commission, the Commissioners, or members of the staff.
Contact information: Lei Fu: leifu1128@gmail.com. Su Li: Office of Asset Management, U.S. Securities and Exchange Commission, 100 F Street, NE Washington, DC 20549, email: lisu@sec.gov, voice: 202-551-7006. David K. Musto: Wharton School of the University of Pennsylvania, 3620 Locust Walk, Philadelphia, PA 19104, email: musto@upenn.edu, voice: 215-898-4239. Neil D. Pearson, Department of Finance, University of Illinois at Urbana-Champaign, 1206 S. Sixth Street, Champaign, IL 61820, email: pearson2@illinois.edu, voice: 217-244-0490.

Hope at a Reasonable Price:
Customer Use of Limit Orders in the 0DTE Market

March 14, 2025

Abstract

Wide quoted spreads and the explosion of 0DTE option trading suggest possible exploitation of customers. In contrast, we find that customers' costs of trading with NMLOs are low. We first identify and correct a sequencing issue in the OPRA trade and quote data that puts the quote that *followed* a trade *before* it and then use quote condition codes to identify customer NMLOs. For the actively traded slightly OTM options, customers are at the BBO more than half the time in recent data. A large fraction of volume is due to customer NMLOs, which execute at low cost.

JEL codes: G12, G13, G23

Keywords: 0DTE options, options trading, OPRA, non-marketable limit orders

1. Introduction

Trading in options expiring the same day, known as zero-date or just 0DTE options, took off during the pandemic to reach 43% of trading in the most popular series, the Cboe's SPXW (i.e., S&P 500) options (Cboe 2023). This trade concentrates in slightly out-of-the-money (OTM) options whose low values and long odds invite comparisons to lottery tickets, and the wide quoted spreads for these low-value options would mean large wealth transfers to market makers if customers traded with marketable orders. However, customers do not have to pay what market makers charge but can instead compete with them by submitting their own *non*-marketable *limit* orders (NMLOs). To see how customers ultimately fare, we analyze transactions in the SPXW limit-order book (LOB), where we find widespread and significant savings through NMLOs. We find that customers are frequently at the Best Bid and Offer (BBO) and we put a high lower bound on the fraction of trades that execute against this liquidity supply. We find that the average transactions cost of these NMLOs is low even when we add an upper bound on the cost of the NMLO not getting executed. We conclude that any exploitation of customers by market makers is much less than first appears.

There are two keys to our analysis. The first is the discovery and correction of an endemic issue in the data. The issue is the sequencing of trades vs. the BBOs that result from the trades in the LOB data reported by the Options Price Reporting Authority (OPRA). When a trade results in a new BBO by consuming depth at the existing BBO, the new BBO typically gets an *earlier* time stamp than the trade itself. So, when the trade price is compared to the BBO that looks like it came *before* it, as in Beckmeyer, Branger and Gayda (2023), it is actually being compared to the BBO that came *after* it. *All* trades on the SPXW LOB consume depth at the BBO so any analysis of trading SPXW options with limit orders must start by putting the trades and BBOs back into the order in which they occurred.

With the data back in the right order we can see how traders compete to provide liquidity. Competing to provide liquidity for SPXW options means contending not only with high-speed competitors but also with price-time priority that heightens their advantage. Customers can gain price-time advantage for themselves by improving on the BBO with *market-turning* NMLOs (MTOs), but this requires that they improve the prices by either \$0.05 or \$0.10, depending on the price of the option. They can instead price at the existing BBBO or worse, so that their orders fill only when the earlier orders at the same price have been filled or cancelled. That is, they can trade by waiting to be picked off. The success of these two tactics, improving on the market to be first in line vs not improving and waiting, determines the viability of trading with NMLOs.

The second key to our analysis is a novel use of OPRA's quote condition codes to identify the limit orders of customers, as opposed to those of market-makers or other exchange members. Quote condition codes tell us whether a customer is somewhere in line at the best bid and/or offer, and we identify two common scenarios where we can deduce that the customer is *first* in line and therefore trades if a marketable order executes against the quote. One scenario is where the quote condition code reveals that an MTO contains customer interest, so a customer is first at that price and thus first in line. The other scenario is when a customer is the last one standing at a price. If the depth at the best bid or offer shrinks to one contract and the code says it's a customer, then that customer has become first in line. Since executing against the last order standing is often referred to as picking it off, we call these pick-off or PO orders. These two order types, MTOs and POs, which turn out to account for a large fraction of LOB trading, are the order types we analyze.

The sample period is the 39 months running from July 1, 2020, through September 28, 2023. We divide this into two subperiods, the periods before and after the introduction of the Tuesday and Thursday expirations of SPXW options. The second period begins on April 25, 2022, the first day of the first week with a Tuesday expiration. The 0DTE week was completed a few weeks later with the first Thursday expiration.

Our first main finding is the high incidence of customer NMLOs in quotes and trades. In the most active range, slightly out-of-the-money, options have customer interest at the best bid more than half the time, and well out-of-the-money options have customer interest at the best offer more than 80% of the time. Most trades occur at quotes with customer interest, which means customers *may* have provided the liquidity, and a quarter of all 0DTE trades are customer MTOs and POs that got filled. Most of these are retail-sized trades for one or only a few contracts, consistent with a large retail order flow through NMLOs rather than marketable orders.

How much does trading with MTOs cost? We measure this in two ways, one taking the customer's perspective and the other taking the counterparty's perspective. We take the customer's perspective by relating the price at which an MTO fills to the midpoint of the BBO prevailing at submission. This "effective spread" takes the customer's perspective by putting the result of the order in the context of the customer's decision to submit it in the first place. This measurement must also address the risk of the order *not* filling, which we do by assuming that the customer waits one second for the MTO to fill and then replaces it with a marketable order if it does not fill. Even with this mechanical use of marketable orders, the customers' gains from trading with MTOs prove to be substantial.

The case of a customer buying calls trading below \$3 when the spread is two ticks (i.e., 2 × \$0.05 = \$0.10) wide is instructive. A two-tick spread leaves only the midpoint for an MTO, so the effective spread of a filled MTO is zero. We find in this case that 50% of customer MTOs fill in the early period, rising to 62% in the later period. We also find that, relative to the same pre-submission midpoint, the cost of a marketable order replacing an *unfilled* MTO after a second is \$0.056 during the earlier period and then \$0.057 during the latter, i.e., the original \$0.05 half-spread plus a \$0.006 to \$0.007 adverse selection cost arising from the correlation between not getting filled and the market moving away. These numbers imply all-in expected costs of \$0.028 early and \$0.021 late, compared to the \$0.05 cost of trading with a marketable order in the first place. In other words, the high chance that the MTO fills and the low adverse-selection cost when it does not make it far cheaper than a marketable order. We find the same pattern for *all* cases with two-tick spreads, whether for calls or puts, buys or sells, and prices below \$3 with a \$0.05 tick size or above \$3 with a \$0.10 tick size. In all cases, there is a strong chance the MTO gets filled and only mild adverse selection when it does not, resulting in expected costs around half that of a marketable order, and cheaper in the later half mostly due to a larger chance that the MTO fills.

Spreads wider than two ticks let the customer choose how much to improve on the BBO with an MTO. When spreads are three or four ticks wide, we find that bigger improvements lead to both higher fill rates and higher adverse selection conditional on not getting filled, as one would expect. We also find that all-in costs are always significantly lower than for marketable orders. As with the two-tick spreads, fill rates increase over time, especially for the MTOs that make smaller improvements to the BBO. The rising fill rates for small improvements are consistent with market makers viewing the order flow as increasingly uninformed, consistent with the increased retail trading.

We also take the *counterparty's* perspective on a trade's cost by computing *realized* spreads that relate the trade price to *subsequent* BBO midpoints, both one second and one minute after the trade. By a second after filling an MTO, the counterparty's trading revenue by this measure is around 2.5 cents in the early period and half that in the later period. By a minute after, the trading revenue is below a penny in the later period. So the customers' counterparties do gain from executing against the MTOs, but much less than even a $0.05 tick.

Our evaluation of trading with POs rather than MTOs includes realized but not effective spreads, since we can track a filled PO forward to subsequent BBOs but we cannot track it back to its submission. Our inability to track it back is not a big loss, since intuitively the risk of trading by being the last at a price is the risk of trading when the market moves the other way, and to measure that risk we need to look forward, not back. We find that POs are more costly by this measure than the less-aggressive MTOs but near the cost of more-aggressive MTOs.

We document this large volume of customer trading through NMLOs on the LOB, but how much of it is *retail* customer volume? A large volume of retail trades on the LOB runs counter to the assumption in Beckmeyer et al (2023) that retail orders are largely sent instead to the Price Improvement Auction (PIA). In a different context, trading of single-name options, Bryzgalova, Pavlova, and Sikorskaya (2023) also assume that retail orders generally go to PIAs. Brokers *can* send retail customers' *marketable* orders to a PIA, but *not* their *non*-marketable orders. Brokers can send marketable orders to the PIA along with contra orders for themselves, and they can also self-route small (up to five contracts) marketable orders, provided their associated market maker is at the NBBO, but they must send the *non*-marketable orders to the LOB where they play out as we document. While we cannot directly identify the retail orders on the LOB, we can identify retail-*sized* orders. We find that 66% of MTO and 68% of PO trades are for the minimum one contract, and an additional 23% and 21% are for two through five contracts. Based on these results and the much larger volume on the LOB than the PIA, we conclude that there is likely much more retail trading through NMLOs on the LOB than retail trading with marketable orders on the PIA.

A consistent pattern in these results is a decline in transaction costs over time, indicating growth in competition to provide liquidity to the 0DTE market. Another way to see this growth is to compare the distribution of BBO sizes, measured in ticks, between the early and late periods. To perform this comparison, we track this distribution for at-the-money options across the trading days of July 2020 and July 2023 and find wide BBO spreads in the early month. For example, in July 2020 the BBO at around 1:00 pm for ATM options is one tick wide just 0.5% of the time and three or more ticks wide 76% of the time. By July 2023 the BBO is one tick wide 64.7% percent of the time, two ticks wide 35.3% of the time, and only rarely wider than two ticks. So where the customers could initially expect to be able to compete using NMLOs placed inside the spread, often with a choice of prices, the situation was different in July 2023. By then, competition filled the LOB so much that customers were often unable to place MTOs inside the spread, and when they were able to do so, except in rare cases the only possibility was to place an order at the midpoint of the two-tick spread.

Other papers on 0DTE options include Brogaard, Han, and Won (2023), who link 0DTE volume to the volatility of the underlying, and Lipson, Tomio, and Zhang (2023) who link single-name retail options trading, not necessarily 0DTE, to underlying stock volatility, arguing that rebalancing hedge trades by negative-gamma market makers increase the volatility. In contrast, Dim, Eraker, and Vilkov (2024) argue that "intraday 0DTE trading volume shocks do not amplify recent past index returns, inconsistent with the view that 0DTEs market growth intensifies market fragility." Adams, Fontaine, and Ornthanalai (2024) provide related evidence associating 0DTE trading with decreases in realized variance. In less closely related work, Bandi, Fusari, and Reno (2023) use time-varying higher moments to price 0DTE options, Almeida, Freire, and Hizmeri (2024) also analyze 0DTE pricing, and Vilkov (2023) calculates returns on simple buy-and-hold trading strategies in 0DTE options.

The role of NMLOs we address resembles their role in the model of Chakravarty and Holden (1995), where NMLOs can undercut the market maker and lead to transactions within the previous BBO spread, though that model does not let the market maker then fill those orders. It is also similar to their role in Foucault (1999), which endogenizes the decision between market and limit orders in a dynamic setting without market makers where limit orders can be picked off by other natural liquidity providers. We find market makers playing both roles, filling MTOs and picking off orders that remain when others leave.

Liquidity providers playing both these roles is explored by the model of Li, Wang, and Ye (2021), which addresses competition for liquidity provision between high-frequency traders (HFTs) and slower execution algorithms (EAs). They identify conditions, such as differences between tick size and bid-ask spread, where EAs may supply liquidity to aggressive orders from HFTs and other EAs. This prediction aligns with our empirical results on customers' MTOs. However, the natural liquidity provider in their model is the EA, which maps most closely to an institutional customer. Our results indicate that retail customers can also be natural liquidity providers.

Our evidence that market makers both supply and demand liquidity in the options market builds on the equity-market research of Brogaard, Hendershott, and Riordan (2015) showing that HFTs' liquidity demands enhance price efficiency by trading in the same direction as permanent price changes and in the opposite direction of transitory pricing errors, while the HFTs' liquidity supply encounters adverse selection. Hendershott and Riordan (2013) observe that HFTs provide liquidity when it is scarce and consume liquidity when it is plentiful.

The SPXW LOB does not allow hidden limit orders, which is why we can learn so much from the BBO. Equity-market LOBs do allow hidden limit orders, and Mclnish and Wood (1995) show that they interact with market orders at prices inside the spread, Shapiro (1993) finds 66% of NYSE trades occur within the spread when it is wider than $0.125, and Bartlett, McCrary, and O'Hara (2022) observe that odd lot quotes create a substantial "inside" market with prices routinely better than the NBBO.

2. Background and Data

2.1 Exchange-listed options on the S&P 500 index

The SPXW options we study settle at 4:00 PM on their expiration dates, in contrast to SPX options that expire in the morning. When SPXW options were introduced in 2005 they expired every Friday. The Cboe introduced SPXW options expiring at quarter-ends in 2006, and other month-ends in 2010. Expirations every Wednesday and Monday began in 2016, and Tuesday and Thursday expirations began in 2022 on April 18 and May 11, respectively. This information is summarized in Table 1.

Panel A of Figure 1 tracks monthly volumes for SPX and SPXW options from 2010 to 2023 and breaks out SPXW volume into volume in 0DTE and non-0DTE expirations. The graph shows relatively stable SPX volume and a surge in SPXW volume after 2020, especially in 2022 when Tuesday and Thursday expirations begin. The shift to 0DTE options is especially noticeable in the percentage shares plotted in Panel B.

SPXW options trade exclusively on the CBOE, which combines electronic trading with floor trading that caters primarily to large institutions and proprietary trading firms. For electronic trades there are LOBs and PIAs for both single- and multiple-leg orders. The SPXW

LOB follows strict price-time priority for execution against marketable orders, with no priority for customers.[1]

The PIA mechanism merits some discussion, as much of the literature appears to oversimplify the PIA process and ignores the fact that customer NMLOs execute in PIAs. For instance, Bryzgalova et. al. (2022) and Hendershott et al. (2024)—although they differ on the level of competition within these auctions—suggest that the only participants are the wholesaler and competing market makers. In this model, once the wholesaler submits a paired order comprising both a customer order and a contra order, the exchange initiates an auction for a customer order which lasts for 100 milliseconds. During this short interval, competing market makers then submit response orders that compete with the contra order to fulfill the customer order. This oversimplified model overlooks the role of passive trading interests, such as market makers' quotes and customers' NMLOs.

According to Cboe's auction manual (Cboe 2024), passive trading interests at the NBBO are automatically included in PIAs. While the submitting wholesaler enjoys some priority over other bidders at the same price, customer NMLOs take precedence over all other trading interests, *including* the submitting wholesaler's contra order at the same price level. Consequently, if a customer NMLO is at the NBBO and neither contra orders nor response orders provide any price improvement relative to the NBBO, the NMLO will receive the allocation before the wholesaler's contra order. Consistent with this, we observe customer auction trades executing against customer NMLOs.

Panel D of Table IA.1 illustrates this scenario with an example. At 13:31:11.851337, a trade marked with the condition code "a" indicates a PIA trade for 2 contracts at $4.60. The quote five microseconds *before* the trade's timestamp shows the depth at $4.60 falling by 2, indicating that this apparently previous quote is actually the quote *caused by* the trade. Furthermore, the previous quote carries a condition code of 'C' indicating customer interest somewhere among the 85 contracts at the bid. The quote when the auction began was one tick wide at $4.60 by $4.70. A logical inference from this fact pattern is that a wholesaler submitted a marketable order to sell 2 contracts at $4.60 to the PIA along with a contra order at $4.60, and the 100 milliseconds saw no better bid, i.e. no bid at $4.70 or better, so customers with NMLOs at $4.60 got the priority and won the auction.

[1] In contrast, the SPX LOB uses pro-rata allocation.

In the later subperiod we find more one-tick quotes and more customer interest at the BBO. This suggests that wholesalers are less inclined to offer prices that improve upon the contemporaneous quotes and that customer NMLOs fill more orders routed to the PIA. We find in Table 4 that the fraction of PIA trades executed between customers—meaning that marketable customer orders are filled by passive customer limit orders— rises from 10% early to 18% late, and that the average spread for the later between-customer trades is only $0.10, compared to the $0.18 average among trades not between customers.

2.2. Data

The primary data are SPXW trades and quotes from the OPRA feed provided by the Market Information Data Analytics System (MIDAS).[2] We collect the data for each combination of SPXW series and date with at least one LOB trade. These data include a record for each trade and each new BBO. The trade records provide trade condition codes indicating the type of trade (i.e., single-leg or complex) and channel (e.g., electronic LOB, PIA, or open-outcry). Some analyses use OPRA trade reports, also from MIDAS. They include each trade record along with the apparently prevailing BBO (which as we discuss below is generally not actually the prevailing BBO) and the BBOs one second and one minute after the trade, which are the BBOs we use to calculate realized spreads.

The quote records include quoted prices, depths, and quote condition codes, which allow us to identify quotes that include customer interest. The key quote condition codes are B, indicating customer interest at the bid, O, indicating customer interest at the offer, C, indicating customer interest at both the bid and the offer, and A, indicating no customer interest at either the bid or the offer. Table 1 displays the trade and quote condition codes.

The sample period runs from July 1, 2020, through September 28, 2023, which we divide into an early and a late period.[3] The early period runs from July 1, 2020 through April 22, 2022, just before Tuesday and Thursday SPXW 0DTE expirations began, and the late period runs from April 25, 2022 through September 28, 2023. In the early period 288 of the 456 trade dates are SPXW expiration dates, and in the late period 355 of the 358 trade dates are SPXW expiration dates.

---

[2] Please see https://www.sec.gov/marketstructure/midas-system.

[3] Our version of the raw OPRA data feed is corrupted on September 29, 2023, so we did not include that trade date in our analysis. The raw OPRA data feed is also corrupted for October 3, 2022, and December 9, 2022.

Table 2 uses the trade condition codes to summarize the distribution of SPXW trading across protocols. It shows that LOB volume is by far the biggest part, though PIA volume picked up from early to late as retail trading grew.

2.3 Putting Trades and Quotes in the Correct Order

Every trade causes an immediate change in the BBO and a new quote record, because every trade consumes some or all of the size available at either the bid or the offer. The new BBO caused by a trade tends to get an earlier time stamp than the trade itself, with the result that time stamps make the BBO following the trade appear to be the BBO that prevailed when the trade was submitted. To illustrate the magnitude of the problem we pick a random date in our sample period, July 1, 2022, and calculate how many trades on the LOB appear to execute strictly inside the BBO, which is not actually possible since all marketable orders execute against the BBO. We report the results of this analysis in Table 3, which shows the percentages of trades with prices equal to the apparent prevailing best bid, apparent prevailing best offer, within the apparent best bid and offer, and at the midpoint of the apparent prevailing bid and offer. The results in that table show that 38% of both call and put trades appear to do the impossible by executing within the prevailing BBO. Thus, the uncorrected timestamps give a very wrong impression of trades and quotes on the LOB. Internet Appendix Table IA.1 provides several examples of incorrectly ordered trades and quotes.

We fix this problem by identifying the pair of consecutive BBOs that matches a trade and then slotting the trade between the pair. Specifically, we look at five consecutive BBOs: the first BBO with a time stamp after the trade's time stamp and the four BBOs before it. We then look at the four consecutive pairs to find the one where the changes in the BBO prices and quantities are consistent with the price and quantity of the trade, and then put the trade between those two.

The reordering algorithm also must account for the disaggregation of trades that interact with multiple passive orders. For example, if there are two buy orders at the top of the LOB, the oldest for one contract and the second-oldest for two, and a marketable sell order for three contracts hits that bid, then there will be two separate trade records reporting the execution of the two passive orders. These two trade records could cause two revisions to the BBO or just one. Table IA.3 illustrates several of the patterns we observe. Panel A shows two one-contract buys at \$1.65 five microseconds apart which correspond to one BBO revision, so we associate both buys with that one revision. Panel B shows two sells 50 microseconds apart that correspond to two

BBO revisions, so we associate the first sell with the first revision and the second sell with the second. Panel C shows three sells of one contract each, two with identical time stamps and one 10 microseconds later, and the bid depth falling by two and then one more. We associate the first two sells with the first revision and the third sell with the second.

Our algorithm matches 99.9% of trades and finds that the large majority are out of sequence. It also finds that this majority changes across the sample period. For example, during the first sample month July 2020, 89.3% of trades are out of sequence and only 10.6% are in sequence. But as Figure IA.1 illustrates, the fraction in sequence rises to 37.8% by January 2023 and declines back to 16.3% by September 2023.

2.4 Identifying Customer Trades

We identify MTOs and POs through inspection of time series of quotes and codes. We cover identification of MTOs first, and then POs.

An MTO is an NMLO that improves the BBO, which is immediately identifiable as a new BBO with a higher bid or lower offer. A customer MTO is an MTO from a customer, which is also immediately identifiable as an MTO in which the new BBO's condition code indicates customer interest at the newly-improved side, so a B or C if the bid is improved and a O or C if the offer is improved.

We identify customer MTO trades by tracking the BBO and trades forward. If the price of the MTO remains the best price and the condition code continues to indicate customer interest on that side, then we assume the customer order has not been canceled and thus transacts against marketable orders hitting that side of the BBO until its quantity is exhausted. So if the first n trades add up to no more than the size of the MTO and the first n+1 trades add up to more, then the first n trades are considered executions of the customer MTO. There is a scenario where more customer interest arrives after the first order and then the first order cancels before trades arrive, in which case the condition code continues to indicate customer interest but some of those n trades may not be customer trades. Our identification assumes that this scenario is rare.

If the BBO improves on the customer MTO with a higher bid or lower offer, then we stop tracking and do not consider any further trades as executions of the customer MTO.

Sometimes a customer's marketable order exceeds the depth at the best price. After consuming the depth at the best price, any remaining trading interest becomes the best bid if it is a buy, or the best offer if it is a sell. This resembles a market turning order since the remaining trading interest establishes the best price. However, even though these orders improve the BBO we do not consider them MTOs as they are marketable from the outset. Table IA.4 provides an example of such an order. Two buys of 3 and 5 at the best offer of $10.00 reduce the depth from 8 to 5 to 0 with the new BBO showing a new best bid with depth of 12. This implies one marketable order for 3 contracts at $10.00 followed by a second for 17 that consumes the 5 and then sets the new best bid for the 12 contracts remaining. This has some of the spirit of an MTO, but since it is partially marketable we do not include it in our analysis of MTOs.

A PO is the last order standing at a quote, and a customer PO is a PO whose condition code identifies it as customer interest. If the remaining depth at a quote is one contract and the condition code identifies it as customer interest, then that one contract is a customer PO. If the remaining depth is more than one contract and the condition code indicates customer interest, then we cannot tell from that information if that depth is one customer PO or several orders which may not all be customer orders. However, if that depth executes as one trade then we know it was one order from a customer since the executions of different orders are reported as separate trades. These are the PO trades we identify: remaining depths of one with customer interest, and larger remaining depths with customer interest that then get filled with one trade.

2.5 *Overview of 0DTE Prices and Quotes*

For a sense of the relevant prices we track across the trading day the average price of 0DTE calls in different moneyness ranges. The strikes of 0DTE options are multiples of $5, which since the S&P is around 4,000 in our sample period is around 0.125% of moneyness. For each minute of the day, and for each day of January 2023, we calculate the average price of six calls: the one whose strike is between $0 and $5 in the money and the next five higher strikes to the strike between $20 and $25 OTM. We then average across days to yield six lines tracking these six moneyness ranges across the average day of January 2023 and add a horizontal line at the $3 dividing line between $0.10 and $0.05 ticks. In the resulting graph, Figure 2, we see that calls $15 to $20 OTM, i.e. around 0.375% to 0.5% OTM, fall into the $0.05 tick range in the middle of the trading day, and the calls just OTM do not reach that range until the last hour.

For a sense of BBO widths across the trading day we calculate, for each minute of the day, the fraction of that minute that the BBO for the call closest to the money is one tick, two ticks, three ticks, etc, wide. We do this for all the days of July 2020 near the beginning of our sample period and all the days of July 2023 near the end and average across the days within those months. The resulting graphs in Figure 3 show spreads narrowing significantly. In July 2020 the most common widths are three and four ticks and one-tick BBOs are rare. In July 2023 the most common widths are one and two ticks, with almost no incidence of wider BBOs before the end of the day. This indicates increasing competition to provide liquidity to the 0DTE market as it gained popularity.

3. Customer Use of Non-Marketable Limit Orders

We begin our analysis by asking how often customers are present at the bid or offer and how their presence varies with moneyness. We then calculate the LOB trading volume that *may* have involved customers because it was against quotes with customer interest, and finally calculate the volume that *did* involve customers because it was against customer MTOs or POs.

3.1 Customer Presence at the BBO

How often are customers at the best bid or offer for an option, and how does their presence depend on moneyness? To find out we calculate, for each 0.125%-wide moneyness bin from 2.5% OTM to 2.5% ITM, the fraction of the trading day that a call in that bin had 1) customers at just the bid, 2) customers at both the bid and the offer, 3) customers at just the offer, and 4) no customers at either the bid or the offer. We do the same for puts, and to capture the change through time we repeat the exercise for the same months from Figure 3, i.e. July 2020 and July 2023. Results for call and puts during July 2020 are plotted in Figure 4, Panels A and B, respectively. Results for calls and puts during July 2023 are plotted in Panels C and D.

The figures show increasing customer presence at the bid, peaking near 40% of the day in July 2020 and 60% in July 2023 for both calls and puts. Peak customer interest moves closer to the money from 1.0-1.5% OTM to 0.5-0.75% OTM, possibly reflecting the lower VIX in July 2023. Customer presence at the offer grows as well, especially for the far OTM options for which there is often no bid and an offer at the minimum \$0.05. Almost all customer interest is for OTM options; their interest in options more than 0.5% in the money is negligible.

3.2 Customer Trading through NMLOs

Does the customers' presence at the BBO lead to customer trades? We answer this question in two steps. The first step is to calculate the incidence of LOB trades that *may* have been customer trades because customers were somewhere in line at the quote the trades executed against. The second step is to calculate the incidence of LOB trades that *were* customer trades because the customers were *first* in line with MTO or PO orders.

We track all three types of executions of limit orders resting on the LOB. The main type is marketable orders sent to the LOB but there are also legs of complex orders, which we call COM orders, and orders sent to the PIA, i.e., PIA orders, which interact with the LOB when they are marketable against it. We check every trade of each type for customer interest at the quote it executes against. If there was customer interest it is a BCO trade, otherwise it is an A trade. A BCO trade *may* be against a customer if it is type LOB or COM, but it is *definitely* against a customer if it is type PIA because customers get priority in the auction. An A trade definitely does *not* involve a customer NMLO. In the case of an LOB or COM trade against a BCO we check further to see if the BCO is an MTO or PO and therefore definitely a customer. Results are in Table 4.

In the main case of trades against LOB orders we find that a majority are BCO trades that may be against customers, and of that majority, most are MTO and PO trades that are definitely against customers. The fraction of LOB trades that are BCO is near 60% in both periods, and of those, 81% and then 69% are MTO or PO. In the smaller set of COM trades, almost half are BCO and the fraction that are MTO or PO is 59% and then 37%. Among PIA trades, BCO trades that definitely involve customer NMLOs rise from 10% to 18%.

We find that customers trading with NMLOs rather than market orders are a big part of the 0DTE market. They are often present at the BBO for the most popular strikes, the trades that are definitely theirs are a large fraction of all LOB trades, and many more trades may also be theirs. Next we consider the effective spreads of the MTOs.

4. Transactions Costs of Customer MTOs

In this section we compare the effective spreads of customer MTOs to the effective spreads from submitting marketable orders instead. The effective spread is the difference between the trade price and the fair value of the security, adjusted for trade direction (e.g. Bessembinder and Venkatamaran, 2009). MTOs that do not fill do not have a trade price, so to make the cost of trading with MTOs comparable to the cost of marketable orders we need to assume a price for the MTOs that do not fill. Our choice is to assume that MTOs that do not fill in one second are canceled and replaced with marketable orders that execute at the then-prevailing BBO. That is, we assume that customers try for one second to do better than a marketable order and then give up and switch to a marketable order. This gives us an apples-to-apples comparison to submitting marketable orders in the first place, though it likely understates the full benefit of MTOs.

This calculation benefits from avoiding the bias that comes from not knowing when the order was submitted. For the fair value we use the midpoint of the BBO that our resequencing identifies as the BBO that prevailed when the MTO was placed, as opposed to the BBO that prevailed when the trade happened. The literature out of necessity often uses the BBO that prevailed when the trade happened, but BBOs subsequent to the placement of the MTO are affected, and thus biased, by the MTO. We avoid this bias by using the unaffected, pre-placement BBO, which for brevity we refer to as BBO_0. Since the data do not show us when a PO is submitted we do not address POs in this section.

We also avoid the bias that comes from not knowing the direction of the customer's order. Without this knowledge it is common to assume that trades closer to the bid are customer sells and trades closer to the offer are customer buys, an assumption that biases up the estimated costs of customer trades. But we see directly whether a customer's MTO is at the bid or offer and thus whether a resulting trade is that customer buying or selling. If there is no resulting trade in a second, *then* we assume the customer pays the spread after all by submitting a marketable order.

Our estimate amounts to a probability-weighted average of the effective spread of an execution of the MTO and the effective spread of a marketable order that includes the adverse selection cost of the MTO not getting filled for a second, where the probability is the probability of getting filled in that second and both spreads are relative to the BBO_0 midpoint. We refer to this as the net effective spread.

Using the BBO_0 midpoint in our estimate might at first glance appear to raise endogeneity concerns since, while it is unbiased by the subsequent MTO, it could still be endogenous to it (see, for example, Muravyev and Pearson (2020)). That is, the BBO_0 midpoint could play a role in the decision to submit the MTO, if for example a customer's impression that the BBO_0 midpoint is below fair value encourages the customer to buy. But even if this is true it does not affect the *relative* cost of buying with an MTO vs buying with a marketable order. To see this, note that the net effective spread of a buy MTO and a hypothetical marketable order (MO) to buy submitted at the same time as the MTO can be written as

$$\text{MTO net effective spread} = qP^{\text{MTO}} + (1 - q)O - V,$$

and

$$\text{MO effective spread} = O - V,$$

respectively, where q is the probability that the MTO is filled, P^{MTO} is the MTO price, O is the offer price, and V is the fair value. The cost savings of the MTO is the difference,

$$\text{Cost savings} = (O - V) - (qP^{MTO} + (1 - q)O - V) = q(O - P^{MTO}).$$

The cost savings do not depend on the fair value V, or our estimate of it. Because of this, if the BBO_0 midpoint M is substituted for the fair value we get the same result,

$$\text{Cost savings} = (O - M) - (qP^{MTO} + (1 - q)O - M) = q(O - P^{MTO}).$$

Thus, any potential relation between executions and the error in the midpoint as a proxy for the fair value does not impact the estimates of cost savings.

Given our assumption that customers try an MTO for one second and then switch to a marketable order, a customer's strategy space is simple: choose one of the few ticks inside BBO_0. If BBO_0 is two ticks wide, i.e. \$0.10 wide below \$3 and \$0.20 wide above, then the midpoint is the only choice. If BBO_0 is n ticks wide then there are $n - 1$ choices, and as Figure 3 illustrates, n tends to be small. We limit our analysis to widths of two to four ticks.

Our analysis contends with multiplicative dimensionality by focusing on a representative subset of the results. There are the three BBO_0 widths, and then there are puts vs calls, buys vs sells, \$0.05-wide ticks below \$3 and \$0.10-wide ticks above,[4] and the early period vs the later period, giving us 3 x 2 x 2 x 2 x 2 = 48 cases. We present all the results but, since the results vary little between buys and sells and between calls and puts, and since the lower-priced options attract the most attention, we focus our discussion on buying calls below \$3.

For each of the three BBO_0 widths the first empirical question is how often customers choose the different ticks available. This is trivial when the width is two ticks, but wider ticks offer a choice. Next we ask, for each tick choice, what fraction of MTOs at that tick fill in one second. We calculate this for both partial and complete fills, but since incomplete fills are rare we focus on the complete-fill number. The effective spreads of the fills is immediate from the ticks, e.g. zero for an MTO at the midpoint. For the MTOs that do not fill in a second we get the relevant quote, i.e. the best offer a second after submission for buy MTOs and the best bid for sell MTOs, and calculate its effective spread from the BBO_0 midpoint. Finally we average these effective spreads for each tick choice, giving us the net effective spread of MTOs at that tick.

---

[4] We disregard the edge case where the bid is below \$3 and the offer is above.

Results are in Tables 5 (two ticks), 6 (three ticks) and 7 (four ticks), with the early period in Panel A of the table and the later period in Panel B.

The two-tick results make two main points. The first is that the likelihood of getting filled at the midpoint increases over time. Below \$3 it increases from around 45% to around 60%, and above \$3 it increases from about 60% to 70%, with little difference between calls and puts and between buys and sells. The second is that the adverse-selection cost of not getting filled in a second is small. The case of buying a call with a price below \$3 in the early period is representative. A marketable order submitted initially would by construction have cost \$0.05. We find that a marketable order submitted after not getting filled for a second would have cost \$0.056, consistent with, for example, a 7/8 likelihood that the best offer doesn't change over that second and a 1/8 likelihood it moves away one tick. The other three cases in Panel A show similar results. In the results for prices above \$3 shown in Panels C and D, the cost of a marketable order submitted after an unfilled MTO increases from \$0.10 to \$0.14, consistent with a larger 2/5 likelihood of moving away one tick.

These numbers imply considerable savings from MTOs. A customer in the later period buying a \$1 call when the BBO is two ticks wide can pay one tick by submitting a marketable order or can submit an MTO at the midpoint. The midpoint MTO imparts a 60% chance of paying zero ticks, a 40%(7/8) = 35% of paying that one tick after all, and just a 5% chance of paying two. As a result, the net effective spread of the MTO is less than half the \$0.05 effective spread of the marketable order. Similarly, the net effective spreads of MTOs for options priced above \$3 were less than half the effective spreads of marketable orders, around \$0.04 versus \$0.10.

The three-tick BBOs in Table 6 offer a choice between submitting a less aggressive "one-tick" MTO that improves on the best quote by one tick and a more aggressive "two-tick" MTO that improves it by two. One-tick MTOs naturally see a much smaller likelihood of filling; the news in Table 6 is that this likelihood increased substantially over time, resulting in a much lower expected cost. In the case of buying a call below \$3, the fill rate on a one-tick MTO rises from 22% to 36% while the net effective spread drops from 5.5 to 3.8 cents, and the fill rate on a two-tick MTO rises from 84% to 90% while the net effective spread drops from 3.5 to 3.2 cents. Compared to the 7.5 cent cost of a marketable order in the first place, these are large and growing savings. Looking across the whole set of three-tick results we see the same pattern: fill rates improving and net effective spreads dropping, especially for the one-tick MTOs.

The four-tick BBO results in Table 7 are similar. The fill rates for call buyers at the three ticks are 13%, 52% and 87% early and 33%, 65% and 89% late. Adverse selection rises but not enough to overcome the rising fill rates, so the net effective spreads change from 7.8, 5.4 and 5.8 cents to 5.5, 4.2 and 5.8 cents compared to the 10 cents of a marketable order. We find the same pattern throughout the results: improving fill rates especially for the less aggressive orders, modestly increasing adverse selection and generally decreasing net effective spreads.

Our mechanical one-second rule leaves these estimates of the savings from MTOs short of the savings from more judicious use, depending on a customer's beliefs or impatience. For example, a customer who sees 0DTE options as worth buying only near the bid would benefit from the fill rates we document and not pay the cost of the marketable orders.

5. Estimates of realized spreads

The effective spread takes the customer's perspective by relating the price the customer gets to the quotes the customer saw when sending the order in. The *realized* spread takes the perspective of the *other* side of the trade, potentially a market maker, looking forward to gauge the gain from filling the order. The literature (e.g., Bessembinder and Venkatamaran, 2009) benchmarks this gain to a subsequent BBO midpoint, as this captures the change from the transaction price including the change due to the transaction itself. We can calculate these not only for MTOs but for POs as well, since we do not need the time the order was submitted, only the time the it was filled. We address MTOs and then POs.

5.1 Realized spreads of MTO trades

The realized spreads look forward two distances, one second and one minute. The results for executed MTOs when the BBO is two, three, and four ticks wide are reported in columns (9) and (10) of Table 5-7, respectively. As these are all filled orders there is no adjustment for the probability of filling.

We find that realized spreads are always less than half the quoted spread, generally less than half a tick and often much less than half. They are particularly low for the less aggressive orders for options with five-cent ticks. This includes all the trades below $3 in Table 5 and almost all the one-tick MTO trades below $3 in Tables 6 and 7. The only trades with realized spreads bigger than half a tick are the most aggressive MTOs into the four-tick BBOs in Table 7.

The small realized spreads measured over the next second and minute mean small profits earned by the counterparties of the customers' MTOs. They are consistent with strong competition to trade against customers.

5.2 Realized spreads of PO trades

Since we do not observe the submission of the POs, we do not sort them by the BBO spread at the time of submission, but we do sort them on all the other dimensions. Results are in Table 8.

The realized spreads from picking customers off are close to what we find for MTOs. For options trading on \$0.05 ticks the realized spread is less than half a tick in all sixteen cases, and for options trading on \$0.10 ticks it is less than half a tick in fifteen out of sixteen cases. The cost relative to MTOs depends on the comparison group. The realized spreads of POs are generally bigger than those of MTOs when BBO_0 is two ticks and of the one-tick MTOs when BBO_0 is wider, and near what we find for more aggressive MTOs. The realized spreads of POs also tend to grow from one second to one minute, consistent with POs getting executed as the market moves against the customer, whereas the realized spreads of MTOs tend to shrink from one second to one minute, consistent with a more transitory post-trade movement in the BBO.

While realized spreads take the perspective of the counterparty filling the customer's order, in the case of POs they are our main metric for the customer's perspective as well due to the unavailability of net effective spreads. The realized spreads indicate that, as with MTOs, POs deliver transaction costs well below those of marketable orders when they fill.

Transaction costs look even lower compared to the exposure to the underlying that the options impart. Using an index value of 4,000 an ATM option contract and an absolute delta of ~0.5 per unit of the index, the exposure would cost $0.5 \times \$4{,}000 = \$2000$ per unit of the index. The largest realized spread for PO trades in the second period, 2.8 cents, is only 0.028/2,000 =0.000014, or 0.14 bps, of that. At a delta of 0.25, more representative of the moneyness customers target, this would be $0.028/(0.25 \times 4{,}000) = 0.28$ bps.

6. Conclusion

We identify a previously unrecognized sequencing problem in the trade and quotes provided by OPRA. Quotes that were active on the CBOE *after* trades were executed are reported *before* the trades are reported. In particular, the quote that appears to be the prevailing quote at the time of a trade was actually *caused* by the trade, because each trade consumes at least some of the size at the best quote and thus triggers a quote update. The resulting jumble of timestamps leads to mistaken inferences and calculations in microstructure research. We develop and implement an algorithm that puts trades and quotes back in the right order and combine this improvement with a close reading of quote condition codes, so we can analyze customers' use of NMLOs when they trade 0DTE options on SPXW, the S&P 500 index.

We find that NMLOs impart large savings over marketable orders and that customers accordingly use them intensively. This applies to NMLOs that gain priority by improving on the BBO and also to NMLOs that gain priority by being the last orders standing when others leave. A large fraction of these NMLOs are retail-sized, one or just a few contracts, indicating a large fraction of retail trading through NMLOs rather than through the marketable orders typically associated with the retail public.

The explosive growth of 0DTE options fuels concerns of liquidity providers taking advantage of retail customers. We find that customers making retail-sized orders economize on transactions costs by competing to provide liquidity and that the 0DTE, and we also find this competition growing over time resulting in much tighter spreads by the end of our sample. The retail public may be losing money on these trades but they are not losing it to transactions costs but rather to the usual effect of high demand on supply.

References

Adams, Greg, Jean-Sebastien Fontaine, and Chayawat Ornthanalai. 2024. The market for 0-days-to-expiration: The role of liquidity providers in volatility attenuation. Working Paper, Bank of Canada and University of Toronto.

Almeida, Caio, Gustavo Freire, and Rodrigo Hizmeri. 2024. 0DTE asset pricing. Working Paper, Princeton University.

Bandi, F.M., Fusari, N. and Reno, R., 2023. 0DTE option pricing. *Available at SSRN*.

Bartlett, R.P., McCrary, J. and O'Hara, M., 2022. Tiny trades, big questions: Fractional shares.

Beckmeyer, H., Branger, N. and Gayda, L., 2023. Retail traders love 0DTE Options... But should they?. *But Should They*.

Brogaard, J., Han, J. and Won, P.Y., 2023. How does zero-day-to-expiry options trading affect the volatility of underlying assets?. *Available at SSRN 4426358*.

Brogaard, J., Hendershott, T. and Riordan, R., 2014. High-frequency trading and price discovery. *The Review of Financial Studies*, *27*(8), pp.2267-2306.

Bryzgalova, S., Pavlova, A. and Sikorskaya, T., 2022. Retail trading in options and the rise of the big three wholesalers. *Journal of Finance forthcoming*.

Cboe. 2023. The Rise of SPX and 0DTE Options.

Cboe, 2024. Cboe Options Auction Process.

Chakravarty, S. and Holden, C.W., 1995. An integrated model of market and limit orders. *Journal of Financial Intermediation*, *4*(3), pp.213-241.

Dim, Chukwama, Bjorn Eraker, and Grigory Vilkov. 2024. 0DTEs: Trading, Gamma Risk and Volatility Propagation. Working paper, George Washington University.

Foucault, T., 1999. Order flow composition and trading costs in a dynamic limit order market. *Journal of Financial markets*, 2(2), pp.99-134.

Fu, Lei, Su Li, David K. Musto, and Neil D. Pearson, 2024a. Tick Size, Limit Orders, and Market Fragmentation. Working paper in Progress.

Fu, Lei, Su Li, David K. Musto, and Neil D. Pearson, 2024b. Other Ways of Internalizing Retail Options Orders. Working paper in Progress.

Hendershott, Terrence, Saad Khan, and Ryan Riordan. 2022. Option auctions. Working paper, University of California Berkeley.

Hendershott, Terrence. and Ryan Riordan, 2013. Algorithmic trading and the market for liquidity. *Journal of Financial and Quantitative Analysis* 48(4), pp.1001-1024.

Lakonishok, Josef, Inmoo Lee, Neil D. Pearson, and Allen M. Poteshman. 2007. Option market activity. *Review of Financial Studies* 20, No. 3, pp. 813-857.

Lee, C.M. and Ready, M.J., 1991. Inferring trade direction from intraday data. *Journal of Finance*, 46, No. 2, pp.733-746.

Li, Sida, X. Wang, X. and Mao Ye, 2021. Who provides liquidity, and when?. *Journal of Financial Economics* 141(3), pp.968-980.

Li, Su, David K. Musto, and Neil D. Pearson, 2023. Costs of executing complex options trades. DERA Working paper.

Li, Su, David K. Musto, Neil D. Pearson, and Li Wang. 2024 (in progress). Reversals, complex trades, and earning announcements. Working paper.

Li, Su, Musto, David K. and Pearson, Neil D., 2023. A simple role for complex options. *Available at SSRN 4389657*.

Lipson, Marc. L., Davide Tomio, and Jiang Zhang. 2023. A real cost of free trades: Retail option trading increases the volatility of underlying securities. Working paper, University of Virginia.

McInish, T.H. and Wood, R.A., 1995. Hidden limit orders on the NYSE. *Journal of Portfolio Management* 21(3), p.19.

Muravyev, Dmitriy, and Neil D. Pearson., 2020. Options trading costs are lower than you think. *Review of Financial Studies* 33(11), 4973–5014

OPRA, New OPRA Trade Message Codes, 2019.

Securities and Exchange Commission, Release No. 34-43086, Order approving option market intermarket linkage plan submitted by the American Stock Exchange LLC, the Chicago Board Options Exchange, Inc., and the International Stock Exchange, LLC, 2000.

Securities and Exchange Commission, Release No. 34-43591, Firm quote and trade-through disclosure rules for options, 2000.

Securities and Exchanges Commission, 2004. Competitive Developments in the Options Markets.

Shapiro, J. E., 1993. U.S. Equity Markets: A View of Recent Developments. Working paper, New York Stock Exchange.

Vilkov, Grigory. 2023. 0DTE Trading Rules. *Available at SSRN*.

Figure 1
SPX and SPXW Options Volumes
Panel A of this figure displays the time series of monthly trading volumes for AM-settled SPX options and PM-settled SPXW options, spanning from 2010 to 2023. The volume for SPXW options is further divided into 0DTE and non-0DTE volumes. Panel B converts these volumes into percentages.

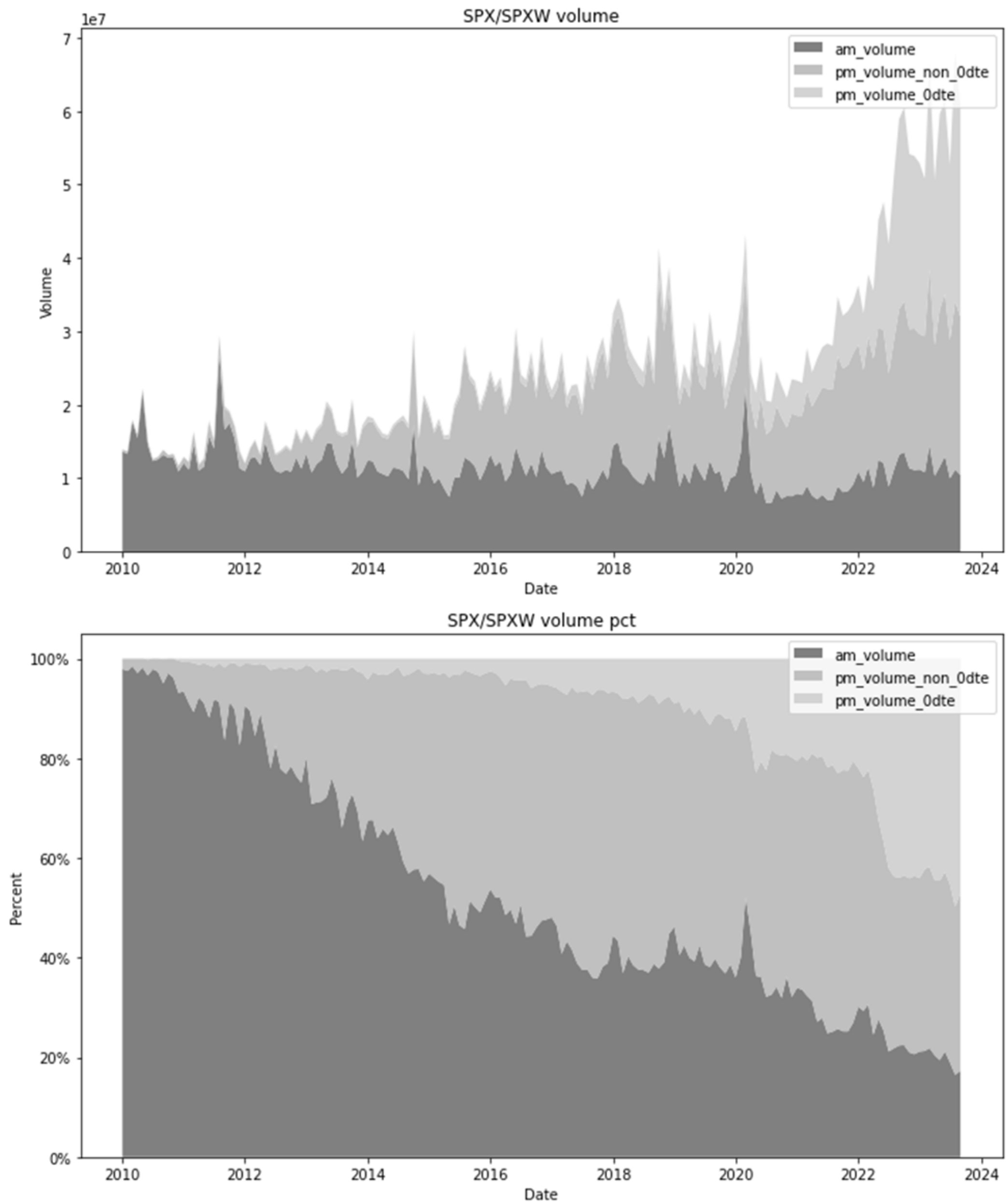


Figure 2
Average 0DTE call options prices during regular trading hours
This figure displays the average prices of 0DTE call options during January 2023 for six different levels of moneyness. For each minute of the day, and for each day of January 2023, we calculate the average price of six calls: the one whose strike is between \$0 and \$5 out of the money, denoted $K = -1$, and the next five higher strikes to the strike between \$20 and \$25 OTM, denoted $K = -2, \ldots, -6$. We then average across days to yield six lines tracking these six moneyness ranges across the average day, through 3:45PM, of January 2023. The horizontal line marks the \$3 dividing line between \$0.10 and \$0.05 ticks.

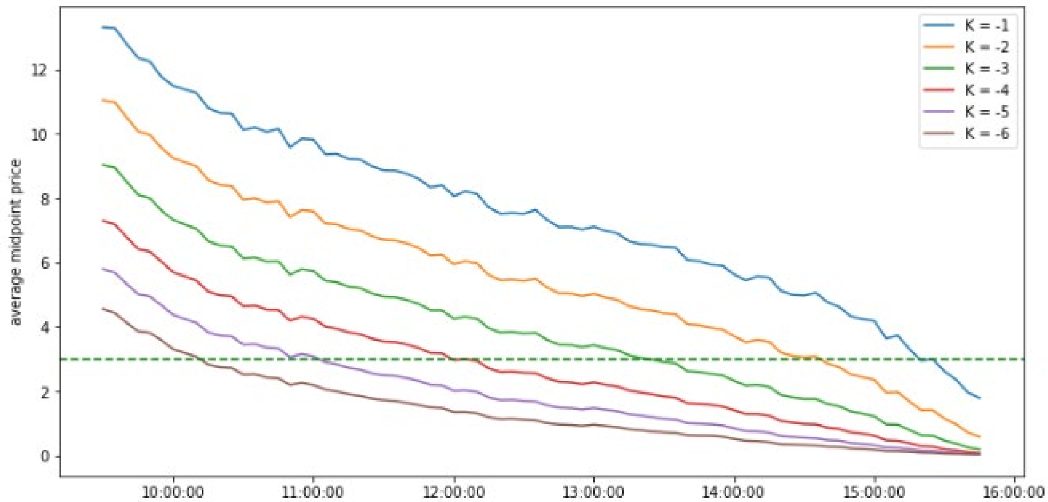


Figure 3
Distribution of spread widths
This figure presents stacked area plots of the distributions of bid-ask spread widths—measured in number of ticks—for ATM calls and puts traded during regular trading hours (9:30 am—4:00 pm) during July 2020 and July 2023. Panels A and B display the intraday tick distribution for ATM calls in July 2020 and 2023, respectively, while Panels C and D do so for ATM puts. The categories range from one tick up to six ticks, with an additional category including all tick widths greater than six.

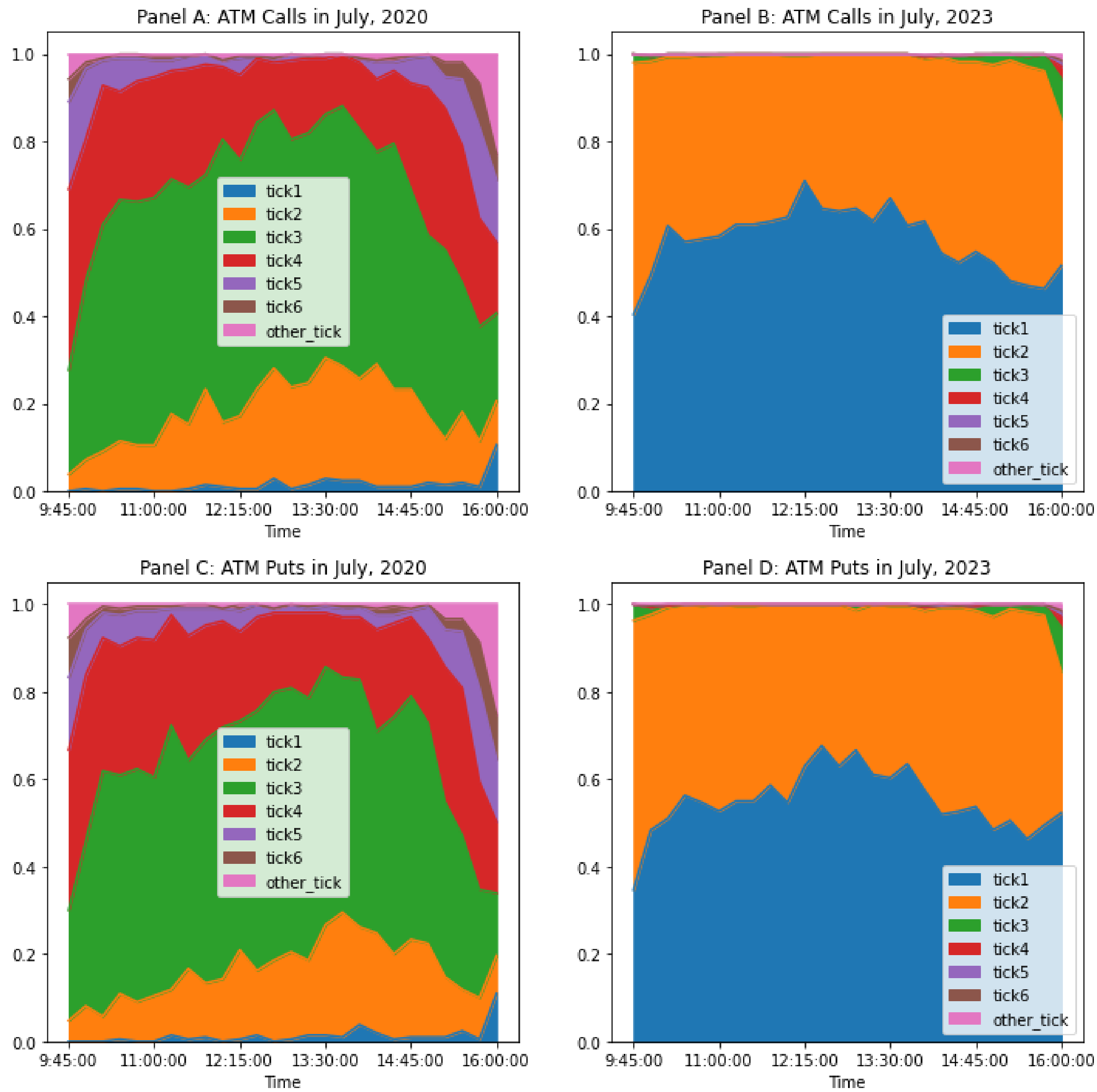
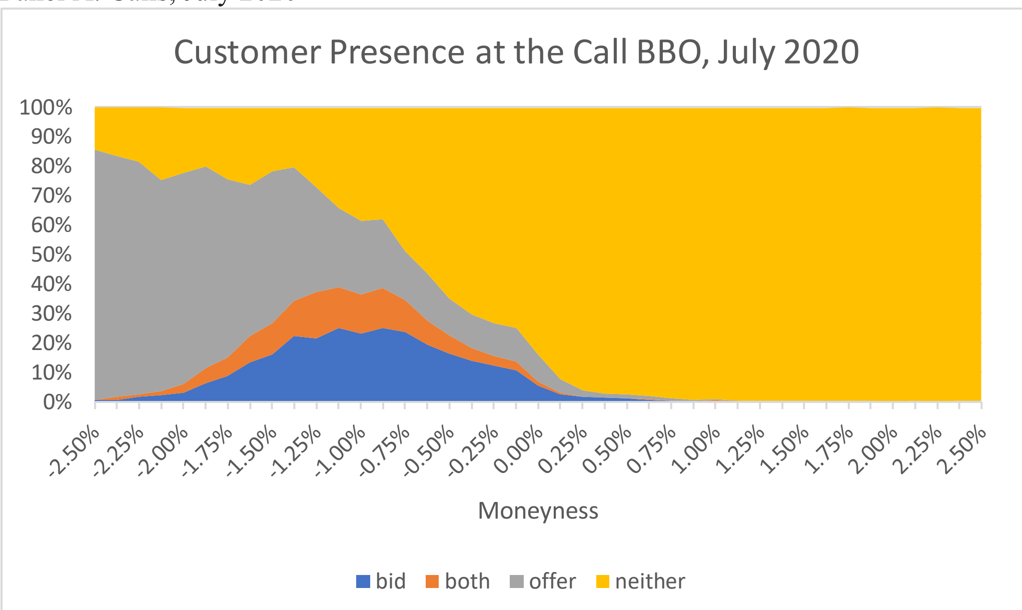


Figure 4
Customer presence at the BBO
This figure displays the fraction of the time when the quote condition codes show that bid, offer, and both the bid and offer include customer interest, for different levels of moneyness. For each 0.125%-wide moneyness bin from 2.5% out of the money to 2.5% in-the-money, we calculate the fraction of the trading day that options in that bin had 1) customers at just the bid, 2) customers at both the bid and the offer, 3) customers at just the offer, and 4) no customers at either. We do this for the trading days in a month early in the sample, July 2020, and a month late in the sample, July 2023. Results for calls and puts during July 2020 are plotted in Panels A and B, while those for calls and puts in July 2023 are in Panels C and D.

Panel A. Calls, July 2020



Panel B. Puts, July 2020

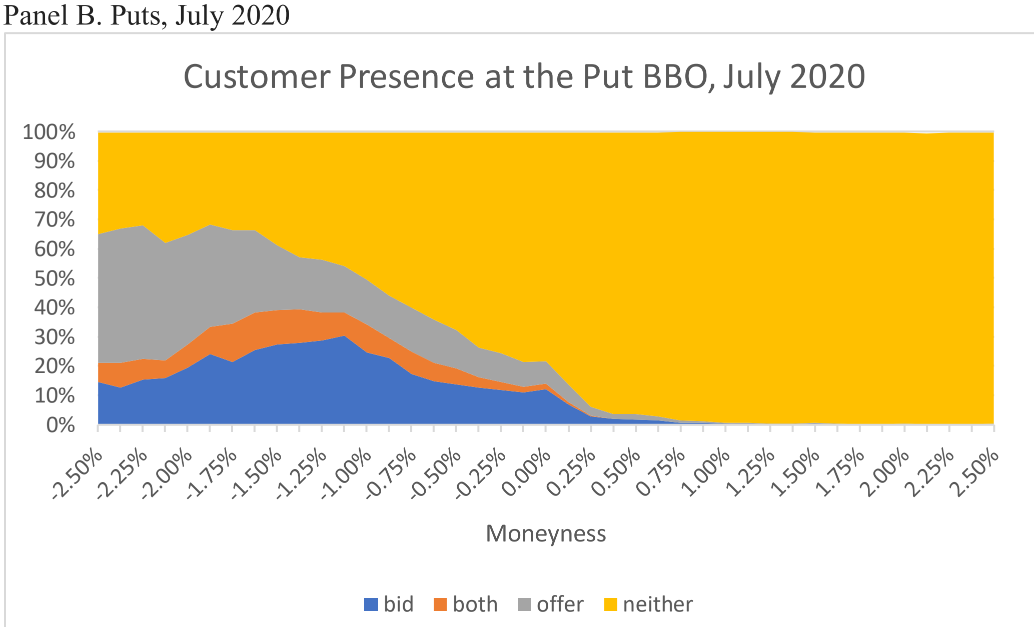
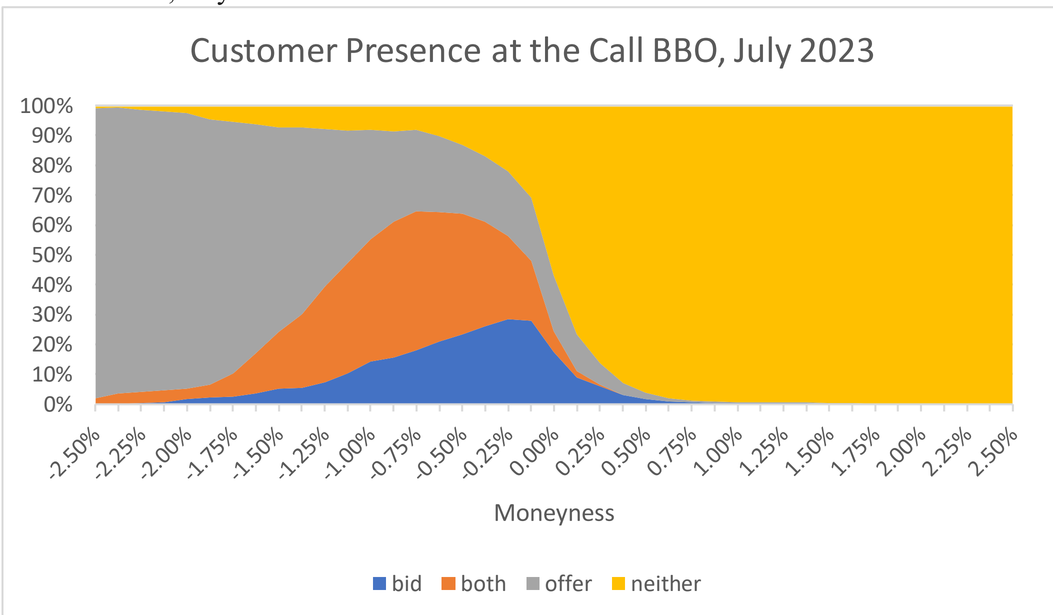


Figure 4 continued

Panel C. Calls, July 2023



Panel D. Puts, July 2023

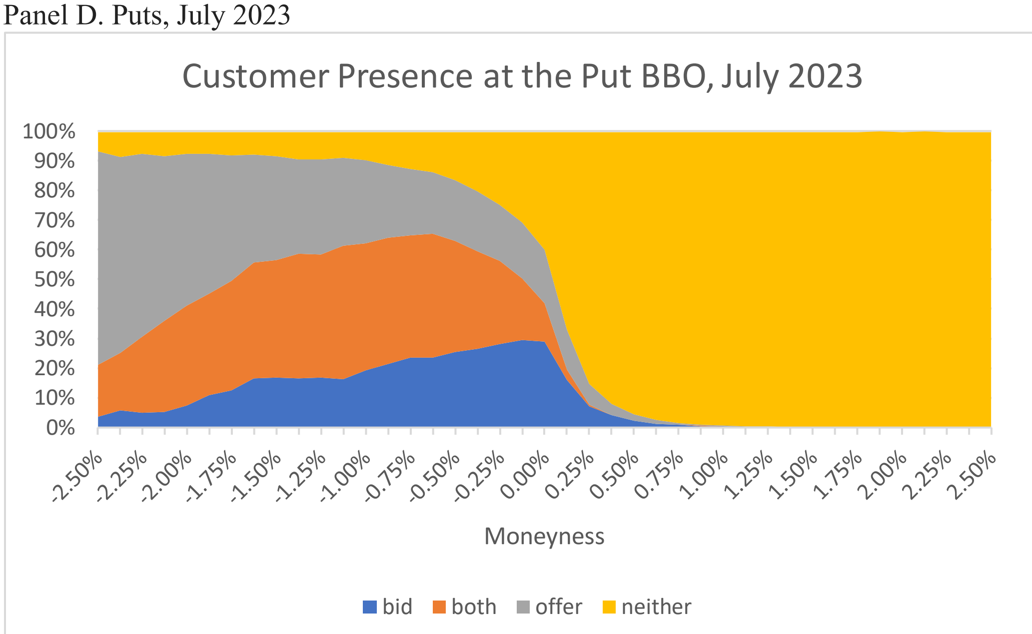


Table 1
Condition Codes for Quotes and Trades from the OPRA Plan, and Settlement and Allocation for S&P 500 Index Options

The table presents background information on the condition codes included in the options quote and trade records per the OPRA plan, as well as settlement and allocation specifics for S&P 500 index options. Panel A details the quote condition codes included with the BBO quote records; Panel B details the trade condition codes for different types of electronic trades; Panel C covers the settlement specifics for SPX and SPXW options; and Panel D describes the allocation algorithm, including the presence of customer priority.

Panel A Quote condition codes

Code	Description
A	Eligible for automatic execution.
B	Bid contains customer trading interest.
O	Offer contains customer trading interest.
C	Both bid and offer contain customer trading interest.

Panel B Trade condition codes

Code	Description
I	Transaction was executed electronically.
S	Transaction was the execution of an order identified as an Intermarket Sweep Order.
a	Single-leg Price Improvement Trade
f	Transaction represents an electronic execution of a multi leg order traded in a complex order book.
g	Transaction was the execution of an electronic multi leg order which was “stopped” at a price and traded in a two-sided auction mechanism that goes through an exposure period in a complex order book.
j	Transaction represents an electronic execution of a multi-leg order traded against single leg orders/ quotes.

Panel C Settlement of S&P 500 options

	Symbol	Settlement			First listed	First settlement
		Date	AM or PM	Type		
SPX traditional	SPX	Third Friday	AM	Cash	7/1/1983	7/15/1983
SPX monthly	SPXW	End of Quarters	PM	Cash	9/22/2006	9/29/2006
		End of other months			1/22/2010	1/29/2010
SPX weeklies	SPXW	Monday	PM	Cash	8/15/2016	8/22/2016
		Tuesday			4/18/2022	4/26/2022
		Wednesday			2/23/2016	3/2/2016
		Thursday			5/11/2022	5/19/2022
		Friday			10/28/2005	11/4/2005

Panel D Allocation

Protocol	Symbol	Allocation	Customer Priority
Single-leg LOB	SPX	Pro-Rata	N
	SPXW	Price-Time	N
Single-leg PIA		Pro-rata/Heightened allocation	Y

Table 2
Summary Statistics of the Trades from the MIDAS Trade Reports Data

This table presents summary statistics pertinent to SPXW options trades from the MIDAS trade reports data. The table is divided into two panels: Panel A focuses on the average daily number of trades, while Panel B details the average daily contract volume. The sample period is further divided into two subperiods: from January 4, 2021, to April 22, 2022, and from April 25, 2022, to September 30, 2023. Within each subperiod, we categorize the SPXW executions by trade type—single-leg and multi-leg (complex)—and further subdivide these into 0DTE and non-0DTE options. Within each expiration category, trades and volumes are broken down by execution protocols: limit order book, auction, and floor.

Panel A Trades

	Single-leg						Multi-leg					
	Non-0DTE			0DTE			Non-0DTE			0DTE		
Period	LOB	Auction	Floor	LOB	Auction	Floor	LOB	Auction	Floor	LOB	Auction	Floor
1	22,949	1,958	86	31,017	3,287	56.5	46,233	5,121	1,099	50,390	4,337	352
2	49,299	7,694	417	163,991	31,169	46.6	67,463	7,319	1,343	118,539	10,294	382

Panel B Contract volume

	Single-leg						Multi-leg							
	Non-0DTE			0DTE			Non-0DTE			0DTE				
Period	LOB	Auction	Floor	LOB	Auction	Floor	LOB	Auction	Floor	LOB	Auction	Floor	0DTE	Sing.-leg
1	164,989	2,944	19,245	142,464	5,102	1,782.5	270,374	8,966	141,379	252,876	8,491	31,043	42.9%	30.98%
2	312,942	10715	27,949	567,788	43,716	3,134.0	349,553	11,967	171,079	461,886	17,973	38,655	55.9%	47.57%

Table 3
Location of trade prices relative to the apparent prevailing BBO
The table displays the results of a comparison of trade prices to the apparent prevailing bid and offer prices from the OPRA quote records, using data from July 1, 2022. It shows the percentages of trades with prices equal to the apparent prevailing best bid, equal to the apparent prevailing best offer, strictly within the apparent prevailing best bid and offer, and at the midpoint of the apparent prevailing bid and offer. It also shows the percentage of trades in the opening session, where best bid and best offer are both 0.

Type	Open	Bid	Offer	Within	Midpoint
C	0.11%	29.93%	32.12%	37.74%	18.42%
P	0.11%	31.53%	30.29%	37.98%	20.28%

Table 4
Analysis of the Trades after Adjusting the Sequences
This table provides an analysis of trade records after applying an algorithm to determine the correct sequence between trade and quote records. We focus on SLOB, SAIM, and SCOM trades, initially categorizing them into "A" trades and "BCO" trades, where "BCO" trades may involve customer limit orders, whereas "A" trades do not. Within the "BCO" category, we further differentiate between trades resulting from market-turning customer limit orders and trades resulting from customer limit orders that are picked-off. For each category or subcategory, we also compute the volume-weighted spread of the correct prevailing quotes and the volume-weighted execution price.

Protocol	Period	0DTE	Total Contracts	A contracts	BCO contracts	A Spread	BCO Spread	A Price	BCO Price	MTO contracts	PO Contracts	MTO spread	PO spread	MTO price	PO price
LOB	1	N	75,176,092	58.73%	41.27%	0.18	0.14	14.24	11.70	70.40%	20.70%	0.12	0.21	10.98	15.80
		Y	410,09,178	40.46%	59.54%	0.18	0.12	4.09	4.46	50.83%	30.36%	0.10	0.17	4.34	5.61
	2	N	111,390,507	67.24%	32.76%	0.15	0.14	14.20	13.18	60.50%	27.60%	0.12	0.19	13.68	15.27
		Y	200,820,711	43.51%	56.49%	0.13	0.10	4.67	4.02	31.10%	38.28%	0.09	0.11	4.71	4.90
COM	1	N	1,392,929	76.50%	23.50%	0.25	0.14	12.51	10.28	73.62%	5.74%	0.15	0.18	12.69	4.12
		Y	2,541,469	53.19%	46.81%	0.17	0.11	2.84	1.85	51.88%	7.25%	0.11	0.18	2.94	1.30
	2	N	1,847,995	79.37%	20.63%	0.15	0.10	8.42	8.34	60.25%	7.00%	0.12	0.10	12.98	1.88
		Y	15,000,290	52.58%	47.42%	0.09	0.07	1.95	1.23	29.46%	8.03%	0.08	0.09	2.77	1.25
PIA	1	N	1,319,837	95.29%	4.71%	0.31	0.15	16.69	6.04						
		Y	1,468,692	90.15%	9.85%	0.26	0.14	6.38	2.96						
	2	N	3,766,086	96.94%	3.06%	0.26	0.12	16.96	4.73						
		Y	15,451,326	82.04%	17.96%	0.18	0.10	6.00	2.49						

Table 5
Effective and realized spreads of MTOs when bid-ask spread is two ticks wide
This table displays estimates of the effective and realized spreads of market-turning orders (MTOs) when the bid-ask spread immediately prior to the MTO is two ticks wide. Panels A and B show the results for options prices less than \$3, for which the tick size is \$0.05, for periods before and after the introduction of the Tuesday and Thursday expirations. Panels C and D show the results for options prices greater than \$3, for which the tick size is \$0.10. Columns (1)-(2) indicate whether the results are for calls (C) or puts (P) and buys or sells, respectively. The "0s" in column (3) indicate that the MTO orders were submitted at the midquote. Columns (4) and (5) show the percentages of the MTOs executed within one second and the average effective spreads of those executions, respectively. Column (6) shows the effective spread of an MO submitted one second after the submission of an unfilled MTO. Column (7) shows the average net effective spread of an MTO, computed as the weighted average of the effective spread of an MTO (column (5)) and the effective spread of an MO submitted after an unfilled MTO (column (6)). For comparison, column (8) shows the effective spread of an MO submitted at the same time as the MTO. Columns (9) and (10) show the realized spreads of executed MTOs, computed using the midpoints one second and one minute after the submission of the MTO, respectively.

C/P	Buy/ sell	Loc. rel. to mid.	% MTOs filled	Eff. sprd. of filled MTO	Eff. sprd. of MO after unfilled MTO	Net eff. sprd. of MTO	Eff. sprd. of MO	Rlzd. sprd. 1 sec.	Rlzd. sprd. 1 min.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: Prior to introduction of Tues. and Thurs. expirations and price < \$3									
C	sell	0	43.6%	0.000	0.055	0.031	0.050	0.000	0.004
C	buy	0	50.2%	0.000	0.056	0.028	0.050	0.002	0.007
P	sell	0	40.2%	0.000	0.054	0.033	0.050	0.000	0.002
P	buy	0	44.0%	0.000	0.055	0.031	0.050	0.002	0.008
Panel B: After introduction of Tues. and Thurs. expirations and price < \$3									
C	sell	0	61.1%	0.000	0.056	0.022	0.050	0.002	0.002
C	buy	0	62.8%	0.000	0.057	0.021	0.050	0.005	0.006
P	sell	0	57.6%	0.000	0.056	0.024	0.050	0.002	0.002
P	buy	0	59.9%	0.000	0.057	0.023	0.050	0.005	0.005
Panel C: Prior to introduction of Tues. and Thurs. expirations and price >\$3									
C	sell	0	57.8%	0.000	0.139	0.059	0.100	0.022	0.018
C	buy	0	60.8%	0.000	0.140	0.055	0.100	0.020	0.012
P	sell	0	58.6%	0.000	0.140	0.058	0.100	0.024	-0.001
P	buy	0	60.0%	0.000	0.141	0.056	0.100	0.020	0.008
Panel D: After introduction of Tues. and Thurs. expirations and price > \$3									
C	sell	0	71.3%	0.000	0.141	0.040	0.100	0.015	0.006
C	buy	0	71.4%	0.000	0.141	0.040	0.100	0.016	0.020
P	sell	0	70.8%	0.000	0.142	0.041	0.100	0.015	0.000
P	buy	0	71.1%	0.000	0.142	0.041	0.100	0.016	0.017

Table 6
Effective and realized spreads of MTOs when bid-ask spread is three ticks wide
This table displays estimates of the effective and realized spreads of market-turning orders (MTOs) when the bid-ask spread immediately prior to the MTO is three ticks wide. Panels A and B show the results for options prices less than $3, for which the tick size is $0.05, for periods before and after the introduction of the Tuesday and Thursday expirations. Panels C and D show the results for options prices greater than $3, for which the tick size is $0.10. Column (3) indicates the aggressiveness of the MTO, where "-1" indicates that the MTO did not cross the previous midquote and "1" indicates that it did. The other columns are described in the legend of Table 5.

C/P	Buy/ sell	Loc. rel. to mid.	% MTOs filled	Eff. sprd. filled MTO	Eff. sprd. of MO after unfilled MTO	MTO net eff. sprd.	MO eff. sprd.	Rlzd. sprd. 1 sec.	Rlzd. sprd. 1 min.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: Prior to introduction of Tues. and Thurs. expirations and price < $3									
C	sell	-1	18.7%	-0.025	0.076	0.057	0.075	0.003	0.007
C	buy	-1	21.9%	-0.025	0.077	0.055	0.075	0.004	0.009
P	sell	-1	16.4%	-0.025	0.076	0.060	0.075	0.007	0.004
P	buy	-1	18.7%	-0.025	0.077	0.058	0.075	0.005	0.007
C	sell	1	80.8%	0.025	0.086	0.037	0.075	0.025	0.020
C	buy	1	83.9%	0.025	0.088	0.035	0.075	0.025	0.013
P	sell	1	81.1%	0.025	0.087	0.037	0.075	0.025	0.016
P	buy	1	83.3%	0.025	0.089	0.036	0.075	0.025	0.016
Panel B: After introduction of Tues. and Thurs. expirations and price < $3									
C	sell	-1	36.9%	-0.025	0.074	0.038	0.075	0.006	0.008
C	buy	-1	36.1%	-0.025	0.074	0.038	0.075	0.005	0.009
P	sell	-1	35.4%	-0.025	0.074	0.039	0.075	0.007	-0.007
P	buy	-1	34.4%	-0.025	0.074	0.040	0.075	0.005	0.004
C	sell	1	87.2%	0.025	0.088	0.033	0.075	0.021	0.018
C	buy	1	89.9%	0.025	0.092	0.032	0.075	0.020	-0.002
P	sell	1	86.9%	0.025	0.088	0.033	0.075	0.022	0.015
P	buy	1	89.5%	0.025	0.092	0.032	0.075	0.022	0.012

Table 6 continued

C/P	Buy/ sell	Loc. rel. to mid.	% MTOs filled	Eff. sprd. filled MTO	Eff. sprd. of MO after unfilled MTO	MTO net eff. sprd.	MO eff. sprd.	Rlzd. sprd. 1 sec.	Rlzd. sprd. 1 min.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel C: Prior to introduction of Tues. and Thurs. expirations and price > $3									
C	sell	-1	28.8%	-0.050	0.168	0.105	0.150	0.023	-0.004
C	buy	-1	30.5%	-0.050	0.168	0.102	0.150	0.027	0.014
P	sell	-1	30.8%	-0.050	0.172	0.104	0.150	0.030	0.014
P	buy	-1	30.3%	-0.050	0.170	0.104	0.150	0.026	0.007
C	sell	1	84.2%	0.050	0.189	0.072	0.150	0.052	0.027
C	buy	1	85.5%	0.050	0.191	0.070	0.150	0.051	0.021
P	sell	1	83.4%	0.050	0.189	0.073	0.150	0.053	0.006
P	buy	1	84.6%	0.050	0.193	0.072	0.150	0.052	0.016
Panel D: After introduction of Tues. and Thurs. expirations and price > $3									
C	sell	-1	43.5%	-0.050	0.183	0.082	0.150	0.019	0.007
C	buy	-1	43.3%	-0.050	0.181	0.081	0.150	0.023	0.022
P	sell	-1	44.7%	-0.050	0.186	0.081	0.150	0.022	0.015
P	buy	-1	43.9%	-0.050	0.183	0.081	0.150	0.022	0.036
C	sell	1	87.1%	0.050	0.197	0.069	0.150	0.034	0.013
C	buy	1	88.8%	0.050	0.202	0.067	0.150	0.038	0.054
P	sell	1	86.5%	0.050	0.196	0.070	0.150	0.038	0.023
P	buy	1	88.3%	0.050	0.204	0.068	0.150	0.038	0.041

Table 7
Effective and realized spreads of MTOs when bid-ask spread is four ticks wide
This table displays estimates of the effective and realized spreads of market-turning orders (MTOs) when the bid-ask spread immediately prior to the MTO is three ticks wide. Panels A and B show the results for options prices less than $3, for which the tick size is $0.05, for periods before and after the introduction of the Tuesday and Thursday expirations. Panels C and D show the results for options prices greater than $3, for which the tick size is $0.10. Column (3) indicates the aggressiveness of the MTO, where "-1" indicates that the MTO did not cross the previous midquote, "0" indicates that it was at the previous midquote, and "1" indicates that it crossed the previous midquote. The other columns are described in the legend of Table 5.

C/P	Buy/ sell	Loc. rel. to mid.	% MTOs filled	Eff. sprd. filled MTO	Eff. sprd. of MO after unfilled MTO	MTO net eff. sprd.	MO eff. sprd.	Rlzd. sprd. 1 sec.	Rlzd. sprd. 1 min.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: Prior to introduction of Tues. and Thurs. expirations and price < $3									
C	sell	-1	12.5%	-0.050	0.097	0.079	0.100	0.006	-0.006
C	buy	-1	13.3%	-0.050	0.098	0.078	0.100	0.005	0.006
P	sell	-1	11.9%	-0.050	0.097	0.080	0.100	0.011	0.001
P	buy	-1	11.5%	-0.050	0.098	0.081	0.100	0.008	0.020
C	sell	0	48.4%	0.000	0.105	0.051	0.100	0.014	0.007
C	buy	0	51.8%	0.000	0.105	0.054	0.100	0.018	0.011
P	sell	0	47.4%	0.000	0.104	0.055	0.100	0.017	-0.001
P	buy	0	49.8%	0.000	0.105	0.053	0.100	0.015	0.013
C	sell	1	84.5%	0.050	0.106	0.059	0.100	0.045	0.036
C	buy	1	86.5%	0.050	0.110	0.058	0.100	0.045	0.038
P	sell	1	83.9%	0.050	0.111	0.060	0.100	0.047	0.043
P	buy	1	86.1%	0.050	0.110	0.058	0.100	0.047	0.035
Panel B: After introduction of Tues. and Thurs. expirations and price < $3									
C	sell	-1	32.5%	-0.050	0.104	0.054	0.100	-0.005	-0.032
C	buy	-1	32.5%	-0.050	0.105	0.055	0.100	-0.006	-0.009
P	sell	-1	30.3%	-0.050	0.103	0.057	0.100	0.001	0.011
P	buy	-1	30.4%	-0.050	0.102	0.055	0.100	0.002	0.029
C	sell	0	63.0%	0.000	0.121	0.042	0.100	0.015	0.037
C	buy	0	65.3%	0.000	0.115	0.042	0.100	0.016	0.013
P	sell	0	61.3%	0.000	0.115	0.044	0.100	0.022	-0.039
P	buy	0	64.0%	0.000	0.120	0.043	0.100	0.009	-0.014
C	sell	1	85.1%	0.050	0.118	0.060	0.100	0.041	0.031
C	buy	1	89.0%	0.050	0.124	0.058	0.100	0.033	0.029
P	sell	1	84.2%	0.050	0.110	0.060	0.100	0.032	0.038
P	buy	1	88.8%	0.050	0.128	0.059	0.100	0.032	0.048

Table 7 continued

C/P	Buy/ sell	Loc. rel. to mid.	% MTOs filled	Eff. sprd. filled MTO	Eff. sprd. of MO after unfilled MTO	MTO net eff. sprd.	MO eff. sprd.	Rlzd. sprd. 1 sec.	Rlzd. sprd. 1 min.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel C: Prior to introduction of Tues. and Thurs. expirations and price > $3									
C	sell	-1	19.2%	-0.100	0.214	0.154	0.200	0.034	0.024
C	buy	-1	19.5%	-0.100	0.214	0.153	0.200	0.040	0.024
P	sell	-1	22.1%	-0.100	0.219	0.149	0.200	0.032	-0.063
P	buy	-1	20.7%	-0.100	0.220	0.154	0.200	0.027	-0.017
C	sell	0	56.9%	0.000	0.236	0.102	0.200	0.037	0.016
C	buy	0	56.9%	0.000	0.236	0.102	0.200	0.043	-0.019
P	sell	0	55.6%	0.000	0.238	0.106	0.200	0.044	0.061
P	buy	0	56.5%	0.000	0.236	0.102	0.200	0.045	-0.015
C	sell	1	84.8%	0.100	0.228	0.119	0.200	0.076	0.026
C	buy	1	84.8%	0.100	0.235	0.120	0.200	0.083	0.018
P	sell	1	81.9%	0.100	0.238	0.125	0.200	0.092	-0.017
P	buy	1	83.7%	0.100	0.238	0.123	0.200	0.087	0.014
Panel D: After introduction of Tues. and Thurs. expirations and price > $3									
C	sell	-1	29.9%	-0.100	0.239	0.138	0.200	0.018	-0.006
C	buy	-1	30.6%	-0.100	0.237	0.134	0.200	0.025	-0.015
P	sell	-1	31.8%	-0.100	0.243	0.134	0.200	0.023	-0.003
P	buy	-1	31.6%	-0.100	0.243	0.134	0.200	0.018	0.036
C	sell	0	65.6%	0.000	0.267	0.087	0.200	0.031	0.018
C	buy	0	67.4%	0.000	0.263	0.091	0.200	0.025	-0.010
P	sell	0	65.7%	0.000	0.269	0.092	0.200	0.026	-0.040
P	buy	0	67.0%	0.000	0.270	0.089	0.200	0.033	0.041
C	sell	1	87.6%	0.100	0.253	0.119	0.200	0.069	-0.004
C	buy	1	89.0%	0.100	0.253	0.117	0.200	0.073	0.086
P	sell	1	86.3%	0.100	0.259	0.122	0.200	0.070	-0.019
P	buy	1	88.0%	0.100	0.263	0.120	0.200	0.061	0.031

Table 8
This table presents the estimates of the realized spreads of PO trades using the BBO midpoint both one second and one minute after the trade. Panel A displays the results for PO trades when the price is less than \$3 and the tick size is \$0.05, and Panel B displays the results when the price is greater than or equal to \$3 and the tick size is \$0.10. In each panel, the estimates are categorized by period, call or put, and trade direction. The table displays the numbers of trades, the mean realized spreads, and the 25th, 50th, and 75th percentiles.

Panel A. Price < \$3

				Realized Spread 1s				Realized Spread 1m			
Period	C/P	Direction	Trades	Mean	P25	P50	P75	Mean	P25	P50	P75
1	C	sell	192,279	0.007	0	0	0.025	0.007	-0.1	0	0.1
		buy	254,432	0.005	0	0	0.025	0.009	-0.075	0	0.1
	P	sell	156,458	0.010	0	0	0.025	0.023	-0.1	0	0.1
		buy	227,574	0.006	0	0	0.025	0.015	-0.05	0.025	0.1
2	C	sell	1,485,037	0.009	0	0	0.025	0.007	-0.125	0	0.1
		buy	2,073,592	0.008	0	0	0.025	0.009	-0.1	0.025	0.125
	P	sell	1,312,936	0.010	0	0	0.025	0.016	-0.125	0	0.1
		buy	1,856,154	0.009	0	0	0.025	0.015	-0.075	0.025	0.125

Panel B. Price ≥ \$3

				Realized Spread 1s				Realized Spread 1m			
Period	C/P	Direction	Trades	Mean	P25	P50	P75	Mean	P25	P50	P75
1	C	sell	327,191	0.031	-0.05	0	0.1	0.025	-0.4	0	0.45
		buy	276,390	0.033	-0.05	0	0.1	0.039	-0.35	0.05	0.45
	P	sell	307,817	0.034	-0.05	0	0.1	0.059	-0.45	0	0.55
		buy	271,421	0.032	-0.05	0	0.1	0.038	-0.4	0.05	0.5
2	C	sell	1,907,701	0.025	-0.05	0	0.1	0.016	-0.4	0	0.4
		buy	1,808,728	0.023	-0.05	0	0.075	0.028	-0.35	0	0.4
	P	sell	1,763,014	0.028	-0.05	0	0.1	0.032	-0.45	0	0.45
		buy	1,716,112	0.024	-0.05	0	0.1	0.042	-0.35	0.05	0.45

Figure IA.1
Fractions of trades that are out of sequence during each month
This table displays the fractions of trades that are out of sequence, in the correct sequence, and unable to be matched, for each month in the sample period running from July 2020 through September 2023.

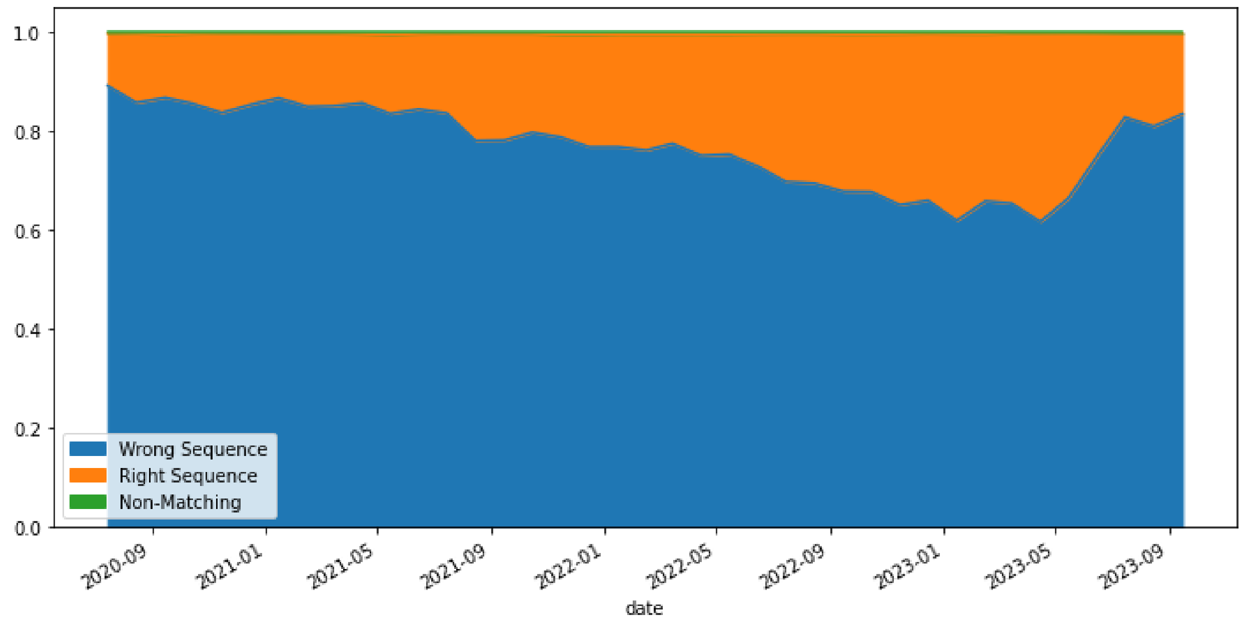


Table IA.1
Sequence Issue in the Raw OPRA Data
The table illustrates the sequence discrepancies between trade and quote records in the raw OPRA data. Panel A provides an example of an "A" trade with adjacent quotes to highlight the sequencing issue. Panel B features an example of a "B" trade resulting from a market-turning customer order. In Panel C displays an example of an "O" trade originating from a non-market-turning customer order, and Panel E displays an example of an "a" (AIM) trade.

Panel A

Quote/Trade	Option	Timestamp	Condition	Bid/Trade Price	Bid/Trade Size	Offer Price	Offer Size
Quote	SPXW__220701C03800000	9:51:31.924789	A	16.9	7	17.2	11
Quote	SPXW__220701C03800000	9:51:31.926638	A	16.9	7	17.2	18
Quote	SPXW__220701C03800000	9:51:31.962764	A	16.8	18	17.2	18
Quote	SPXW__220701C03800000	9:51:32.005540	A	16.8	17	17.2	18
Trade	SPXW__220701C03800000	9:51:32.005560	I	16.8	1		
Quote	SPXW__220701C03800000	9:51:32.008628	A	16.8	10	17.2	25

Panel B

Quote/Trade	Option	Timestamp	Condition	Bid/Trade Price	Bid/Trade Size	Offer Price	Offer Size
Quote	SPXW__220701C03800000	9:51:46.207744	A	17.3	9	17.6	2
Quote	SPXW__220701C03800000	9:51:46.215274	A	17.3	9	17.7	31
Quote	SPXW__220701C03800000	9:51:46.215318	A	17.3	11	17.7	31
Quote	SPXW__220701C03800000	9:51:46.219688	B	17.5	1	17.7	31
Quote	SPXW__220701C03800000	9:51:46.234629	B	17.5	1	17.7	23
Quote	SPXW__220701C03800000	9:51:46.238397	B	17.5	1	17.7	21
Quote	SPXW__220701C03800000	9:51:46.278011	B	17.5	1	17.7	29
Quote	SPXW__220701C03800000	9:51:46.283921	A	17.3	48	17.7	29
Trade	SPXW__220701C03800000	9:51:46.283926	I	17.5	1		
Quote	SPXW__220701C03800000	9:51:46.295535	A	17.3	48	17.7	31

Panel C

Quote/Trade	Option	Timestamp	Condition	Bid/Trade Price	Bid/Trade Size	Offer Price	Offer Size
Quote	SPXW__220701C03800000	9:53:38.298832	A	1.4	151	1.55	53
Quote	SPXW__220701C03800000	9:53:38.341669	O	1.4	151	1.55	54
Quote	SPXW__220701C03800000	9:53:38.372012	O	1.4	151	1.55	1
Quote	SPXW__220701C03800000	9:53:38.372906	O	1.4	166	1.55	1
Quote	SPXW__220701C03800000	9:53:38.404603	O	1.4	169	1.55	1
Quote	SPXW__220701C03800000	9:53:38.473175	O	1.4	169	1.55	13
Quote	SPXW__220701C03800000	9:53:38.524753	O	1.4	169	1.55	29
…	…	…	…	…	…	…	…
Quote	SPXW__220701C03800000	9:53:39.697270	O	1.45	17	1.55	29
Quote	SPXW__220701C03800000	9:53:39.738383	O	1.45	17	1.55	17
Quote	SPXW__220701C03800000	9:53:39.738585	O	1.45	17	1.55	1
Quote	SPXW__220701C03800000	9:53:39.797579	O	1.45	18	1.55	1
Quote	SPXW__220701C03800000	9:53:39.917165	O	1.5	68	1.55	1
Quote	SPXW__220701C03800000	9:53:39.988549	O	1.5	84	1.55	1
Quote	SPXW__220701C03800000	9:53:39.999936	O	1.5	134	1.55	1
Quote	SPXW__220701C03800000	9:53:40.011449	A	1.5	134	1.6	177
Trade	SPXW__220701C03800000	9:53:40.011454	I	1.55	1		
Quote	SPXW__220701C03800000	9:53:40.011590	A	1.55	1	1.6	177

Panel D

Quote/Trade	Option	Timestamp	Condition	Bid/Trade Price	Bid/Trade Size	Offer Price	Offer Size
Quote	SPXW__230905P04500000	13:31:11.710731	C	4.6	74	4.7	20
Quote	SPXW__230905P04500000	13:31:11.711308	C	4.6	74	4.7	24
Quote	SPXW__230905P04500000	13:31:11.737511	C	4.6	74	4.7	20
Quote	SPXW__230905P04500000	13:31:11.750807	C	4.6	85	4.7	20
Quote	SPXW__230905P04500000	13:31:11.851332	C	4.6	83	4.7	20
Trade	SPXW__230905P04500000	13:31:11.851337	a	4.6	2		
Quote	SPXW__230905P04500000	13:31:12.178849	C	4.6	83	4.8	86

Table IA.2
Time-weighted Quote Analysis
This table provides a time-weighted quote analysis. At the beginning of every minute during RTH, we first compare the index value to the exercise price of the option to calculate the moneyness, K, defined as the greatest integer less than or equal to (index value – exercise price)/5. Through each one-minute interval, we calculate the percentage of time that 'A' quotes, 'B' quotes, 'O' quotes, and 'C' quotes last. Panel A presents the results for SPXW options in July 2020 and Panel B presents the results in July 2023.

Panel A 2020/07

	Call				Put			
K	A	B	O	C	A	B	O	C
-20	14.38%	0.51%	84.78%	0.10%	99.38%	0.02%	0.20%	0.00%
-19	16.37%	0.64%	81.82%	0.94%	99.51%	0.06%	0.07%	0.00%
-18	18.33%	1.69%	78.97%	0.78%	99.54%	0.16%	0.02%	0.00%
-17	24.48%	2.29%	71.85%	1.18%	99.42%	0.00%	0.03%	0.00%
-16	22.17%	3.13%	71.65%	2.80%	99.53%	0.17%	0.06%	0.00%
-15	19.91%	6.21%	68.44%	5.19%	99.56%	0.00%	0.00%	0.00%
-14	24.21%	8.74%	60.58%	6.22%	99.51%	0.01%	0.18%	0.00%
-13	26.08%	13.37%	51.42%	8.88%	99.37%	0.05%	0.24%	0.00%
-12	21.50%	16.13%	51.59%	10.53%	99.25%	0.25%	0.26%	0.00%
-11	20.26%	22.42%	45.26%	11.80%	99.57%	0.09%	0.12%	0.00%
-10	27.06%	21.45%	35.50%	15.74%	99.34%	0.10%	0.31%	0.04%
-9	33.93%	24.96%	27.05%	13.80%	99.35%	0.13%	0.35%	0.01%
-8	38.48%	23.21%	24.97%	13.09%	99.20%	0.22%	0.38%	0.01%
-7	37.85%	25.15%	23.36%	13.39%	98.52%	0.63%	0.65%	0.01%
-6	48.72%	23.73%	16.41%	10.88%	98.36%	0.69%	0.72%	0.03%
-5	56.30%	19.19%	15.90%	8.35%	97.08%	1.39%	1.20%	0.08%
-4	64.74%	16.43%	12.44%	6.13%	96.23%	1.60%	1.86%	0.08%
-3	70.17%	13.98%	11.21%	4.39%	96.19%	1.83%	1.63%	0.10%
-2	73.09%	12.18%	11.02%	3.46%	93.70%	2.79%	2.89%	0.37%
-1	74.75%	10.75%	11.48%	2.76%	86.04%	6.82%	6.05%	0.84%
0	83.67%	5.60%	9.31%	1.17%	78.15%	12.07%	7.72%	1.80%
1	91.97%	2.48%	4.83%	0.47%	78.53%	11.04%	8.29%	1.88%
2	95.77%	1.58%	2.25%	0.15%	75.52%	11.91%	9.66%	2.65%
3	96.85%	1.34%	1.41%	0.14%	73.43%	12.68%	10.20%	3.44%
4	97.32%	1.25%	1.16%	0.01%	67.63%	13.79%	12.96%	5.36%
5	97.81%	0.68%	1.20%	0.06%	63.93%	14.80%	14.64%	6.38%
6	98.73%	0.45%	0.59%	0.00%	59.99%	17.32%	14.84%	7.60%
7	99.07%	0.22%	0.47%	0.00%	55.85%	22.59%	14.30%	6.99%
8	98.95%	0.46%	0.34%	0.01%	50.38%	24.48%	15.28%	9.63%
9	99.29%	0.21%	0.24%	0.00%	45.78%	30.39%	15.63%	7.94%
10	99.27%	0.11%	0.33%	0.01%	43.44%	28.64%	18.14%	9.52%
11	99.40%	0.17%	0.16%	0.00%	42.59%	27.81%	17.84%	11.50%
12	99.47%	0.15%	0.13%	0.00%	38.65%	27.29%	21.92%	11.86%
13	99.36%	0.20%	0.15%	0.00%	33.37%	25.51%	28.17%	12.70%
14	99.56%	0.18%	0.12%	0.00%	33.38%	21.36%	31.95%	13.06%
15	99.21%	0.36%	0.08%	0.00%	31.40%	23.94%	34.97%	9.44%
16	99.51%	0.09%	0.09%	0.00%	34.97%	19.45%	37.53%	7.80%
17	99.38%	0.32%	0.03%	0.00%	37.76%	15.85%	40.20%	5.93%
18	99.65%	0.12%	0.04%	0.00%	31.85%	15.20%	45.40%	7.29%
19	99.53%	0.18%	0.03%	0.00%	32.76%	12.69%	45.80%	8.51%
20	99.42%	0.08%	0.20%	0.00%	34.82%	14.47%	43.89%	6.57%

Panel B 2023/07

	Call				Put			
K	A	B	O	C	A	B	O	C
-20	0.77%	0.11%	97.01%	1.86%	99.65%	0.09%	0.02%	0.00%
-19	0.48%	0.07%	95.75%	3.46%	99.59%	0.03%	0.01%	0.00%
-18	1.24%	0.34%	94.39%	3.76%	99.73%	0.01%	0.00%	0.00%
-17	1.61%	0.59%	93.42%	4.12%	99.80%	0.00%	0.00%	0.00%
-16	2.24%	1.78%	92.47%	3.25%	99.70%	0.04%	0.02%	0.00%
-15	4.25%	2.24%	88.93%	4.31%	99.64%	0.09%	0.05%	0.00%
-14	5.24%	2.45%	84.25%	7.80%	99.58%	0.07%	0.07%	0.00%
-13	5.99%	3.44%	76.78%	13.53%	99.62%	0.06%	0.05%	0.00%
-12	7.07%	5.14%	68.53%	19.00%	99.66%	0.04%	0.04%	0.00%
-11	6.94%	5.28%	62.68%	24.83%	99.55%	0.10%	0.08%	0.00%
-10	7.53%	7.18%	52.73%	32.30%	99.53%	0.10%	0.10%	0.00%
-9	8.14%	10.10%	44.36%	37.13%	99.47%	0.14%	0.13%	0.00%
-8	7.85%	14.16%	36.56%	41.16%	99.21%	0.27%	0.26%	0.00%
-7	8.34%	15.50%	30.41%	45.49%	98.90%	0.45%	0.37%	0.01%
-6	7.99%	17.88%	27.06%	46.81%	98.22%	0.82%	0.69%	0.00%
-5	9.94%	20.82%	25.59%	43.38%	97.37%	1.20%	1.16%	0.01%
-4	12.93%	23.33%	23.17%	40.31%	95.47%	2.29%	1.96%	0.04%
-3	16.57%	26.08%	22.03%	35.06%	91.90%	4.06%	3.63%	0.14%
-2	21.84%	28.33%	21.52%	28.05%	85.09%	6.98%	7.07%	0.59%
-1	30.66%	27.91%	21.19%	19.99%	66.66%	16.09%	13.57%	3.41%
0	56.51%	17.46%	18.73%	7.02%	39.64%	28.99%	18.25%	12.84%
1	76.42%	8.92%	12.31%	2.09%	30.72%	29.54%	18.84%	20.64%
2	86.01%	5.86%	7.29%	0.57%	24.70%	28.12%	18.92%	28.00%
3	92.82%	2.96%	3.79%	0.16%	20.09%	26.47%	20.30%	32.88%
4	95.87%	1.55%	2.27%	0.05%	16.20%	25.44%	20.48%	37.62%
5	97.83%	0.92%	0.98%	0.01%	13.62%	23.45%	20.88%	41.78%
6	98.55%	0.51%	0.67%	0.00%	12.47%	23.50%	22.32%	41.45%
7	99.00%	0.33%	0.40%	0.00%	11.20%	21.42%	24.39%	42.72%
8	99.08%	0.27%	0.39%	0.00%	9.68%	19.27%	27.91%	42.87%
9	99.08%	0.29%	0.37%	0.00%	8.70%	16.11%	29.60%	45.32%
10	99.15%	0.27%	0.33%	0.00%	9.17%	16.87%	32.18%	41.52%
11	99.23%	0.23%	0.28%	0.00%	9.32%	16.60%	31.83%	41.98%
12	99.42%	0.16%	0.15%	0.00%	8.28%	16.77%	34.99%	39.71%
13	99.53%	0.12%	0.09%	0.00%	7.74%	16.50%	36.49%	39.01%
14	99.59%	0.08%	0.07%	0.00%	7.86%	12.34%	42.42%	37.12%
15	99.69%	0.03%	0.03%	0.00%	7.33%	10.89%	47.29%	34.23%
16	99.70%	0.03%	0.03%	0.00%	7.39%	7.47%	51.36%	33.51%
17	99.69%	0.02%	0.02%	0.00%	8.08%	5.26%	55.82%	30.57%
18	99.69%	0.01%	0.01%	0.00%	7.39%	5.02%	61.89%	25.43%
19	99.68%	0.01%	0.01%	0.00%	8.52%	5.77%	66.09%	19.36%
20	99.69%	0.03%	0.00%	0.00%	6.50%	3.53%	72.22%	17.49%

Table IA.3
Matching Multiple Sequential Trades to the Quotes
This table illustrates sequential trade matching cases with varying trade-quote dynamics across different panels. In Panel A, two 1-contract trades executed within 5 microseconds at $1.65 are matched to the same quote due to the bid depth equaling the total trade size; Panel B shows a 9-contract trade followed by an 8-contract trade separated by an intermediate quote reflecting a stepwise reduction in bid depth; and Panel C presents a scenario where the first two of three trades share one quote while the third trade is matched to a subsequent quote.

Panel A

Quote/Trade	Option	Timestamp	Condition	Bid/Trade Price	Bid/Trade Size	Offer Price	Offer Size
Quote	SPXW__230428C04160000	03:09:23.297057	B	1.65	2	1.75	130
Quote	SPXW__230428C04160000	03:09:24.264833	B	1.65	2	1.7	10
Quote	SPXW__230428C04160000	03:09:24.522567	B	1.6	105	1.7	10
Trade	SPXW__230428C04160000	03:09:24.522572	I	1.65	1		
Trade	SPXW__230428C04160000	03:09:24.522577	I	1.65	1		
Quote	SPXW__230428C04160000	03:09:24.522577	B	1.6	105	1.65	10
Quote	SPXW__230428C04160000	03:09:24.522587	B	1.6	34	1.65	81

Panel B

Quote/Trade	Option	Timestamp	Condition	Bid/Trade Price	Bid/Trade Size	Offer Price	Offer Size
Quote	SPXW__230428C04160000	03:54:34.823073	B	1.35	43	1.45	170
Quote	SPXW__230428C04160000	03:54:34.984779	B	1.4	17	1.45	170
Quote	SPXW__230428C04160000	03:54:37.007710	B	1.4	8	1.45	148
Trade	SPXW__230428C04160000	03:54:37.007720	I	1.4	9		
Trade	SPXW__230428C04160000	03:54:37.007770	I	1.4	8		
Quote	SPXW__230428C04160000	03:54:37.007782	A	1.35	26	1.45	148
Quote	SPXW__230428C04160000	03:54:37.009259	A	1.35	26	1.4	7

Panel C

Quote/Trade	Option	Timestamp	Condition	Bid/Trade Price	Bid/Trade Size	Offer Price	Offer Size
Quote	SPXW__230428C04160000	04:01:48.775519	B	1.1	3	1.15	130
Quote	SPXW__230428C04160000	04:01:54.034760	B	1.1	3	1.15	141
Quote	SPXW__230428C04160000	04:01:54.045506	B	1.1	1	1.15	141
Trade	SPXW__230428C04160000	04:01:54.045510	I	1.1	1		
Trade	SPXW__230428C04160000	04:01:54.045510	I	1.1	1		
Quote	SPXW__230428C04160000	04:01:54.045620	B	1.05	32	1.15	141
Trade	SPXW__230428C04160000	04:01:54.045620	I	1.1	1		
Quote	SPXW__230428C04160000	04:01:54.047496	B	1.05	32	1.15	153

Table IA.4
An Example of Walking-Up the LOB
This table presents an example where a marketable order to buy 17 contracts at $10 exceeds the best offer depth of 5 contracts, leading to a marketable trade at $10 and the remaining 12 contracts becoming the new best bid, a scenario excluded from our market turning order analysis.

Quote/Trade	Option	Timestamp	Condition	Bid/Trade Price	Bid/Trade Size	Offer Price	Offer Size
Quote	SPXW__230103C03805000	14:16:14.876464	A	9.8	49	10	8
Quote	SPXW__230103C03805000	14:16:14.896412	A	9.8	48	10	8
Quote	SPXW__230103C03805000	14:16:15.174184	A	9.8	48	10	5
Trade	SPXW__230103C03805000	14:16:15.174189	I	10	3		
Quote	SPXW__230103C03805000	14:16:15.174465	B	10	12	10.1	50
Trade	SPXW__230103C03805000	14:16:15.174465	I	10	5		
Quote	SPXW__230103C03805000	14:16:15.174650	B	10	12	10.1	47
Quote	SPXW__230103C03805000	14:16:15.176299	A	9.8	44	10.1	47
Trades	SPXW__230103C03805000	14:16:15.176299	I	10	12		
Quote	SPXW__230103C03805000	14:16:15.176479	A	9.8	44	10	13
Quote	SPXW__230103C03805000	14:16:15.177291	A	9.8	45	10	13

Figure IA.1
Percentages of Trades in the Wrong Sequence
This figure displays a monthly stacked area plot showing the percentages of LOB trades that are out of sequence, in sequence, and unmatched with quotes.