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Option Auctions

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Wholesale market makers pay for retail options orders that must be executed on exchanges. Payment for order flow (PFOF) wholesalers compete via price improvement in exchange auctions. To attract retail orders, wholesalers run more auctions when their recent price improvement has been lower. However, auction price improvement lowers market maker revenues. Wholesalers earn revenues to pay PFOF in nonauction trades where their designated market maker status increases their execution priority. While some auctions produce substantial price improvement, most do not have multiple bidders offering meaningful price improvement. Overall, options market structure better promotes competition in auctions than in nonauctions. (*JEL* G14, G11, G12, G20)

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Since directed by Congress in 1975 to create a national market system for financial securities, the U.S. Securities and Exchange Commission (SEC) has attempted to promote competition among investors, broker-dealers, and securities markets. More recently, in 2022 SEC Chair Gensler criticized the practice of selling retail orders (payment for order flow, or PFOF) to wholesale market makers in equity markets, contending that the practice

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creates agency problems between brokers and retail investors.[1] The SEC subsequently proposed on-exchange equity auctions in an effort to increase competition and price improvement for retail orders.[2] We analyze existing on-exchange auctions in equity options to understand options market structure and provide evidence showing how equity auctions may perform.

We study how the order routing of marketable orders, execution costs, and market maker (MM) revenues varies depending on whether the order executes in an auction or in continuous trading and on an exchange where wholesalers are designated market makers.[3] These analyses facilitate three main contributions. First, in-depth analysis of how wholesalers use of option auctions to manage retail execution quality statistics provides evidence as to whether brokers hold wholesalers accountable for execution quality and how wholesalers respond. Second, we provide direct, comprehensive evidence on the potential costs and benefits of auctions similar to those proposed by the SEC for stocks. Third, we examine which types of options trades are most likely to be retail by using both auctions and the wholesaler designated market maker (DMM) assignment.

While PFOF is often associated with stocks, it is more prevalent in options. More than half of option trading involves orders purchased by wholesalers, such as Citadel or Susquehanna, from brokers like Robinhood and TD Ameritrade. Wholesalers also act as DMMs and internalize retail orders in continuous exchange trading.[4] Wholesalers compete for retail orders via price improvement in on-exchange auctions, which account for over 20% of options trading volume. Auctions save investors over $47 million daily via price improvement. However, wholesalers must earn revenues to pay PFOF through internalizing purchased marketable retail orders either in auctions or continuous (nonauction) exchange trading.

Each retail broker sells customers' orders to a set of wholesalers for the same amount per order. Brokers earn PFOF revenues while wholesalers purchasing these orders decide where to route them. Wholesalers maximize revenues by balancing the decision as to whether to offer price improvement in an auction to attract more retail order flow in the future or to internalize the

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1 An agency problem could result if competition between brokers is imperfect. Retail customers may prefer lower PFOF and higher price improvement if competition does not lead brokers to pass PFOF back to the clients through better service or lower commissions. Brokers charge all wholesalers the same PFOF for orders, so brokers do not have agency problems in their routing incentives.

2 Proposed Rule 615 of Regulation National Market System, titled the "Order Competition Rule," https://www.sec.gov/rules/proposed/2022/34-96495.pdf. In 2009, the SEC proposed banning flash orders, an order type on stock exchanges that allowed for price improvement. The exchanges ceased offering flash orders before they were formally banned (Skjeltorp, Sojli, and Tham 2016).

3 Continuous trading occurs immediately upon the arrival of a marketable order, as opposed to the delay that occurs in auctions. Continuous trading involves limit orders as well as market makers and (virtual) floor participants. See Appendix A2 for a detailed discussion of CBOE trading rules.

4 Internalization refers to a broker executing a customer order against their own inventory. In stocks, this occurs off-exchange. Option exchanges have a variety of rules that can give higher execution priority to DMMs and the broker routing the order to the exchange. This enables wholesalers to route orders to exchanges where they can internalize more of a retail order.

order at the posted quotes without price improvement in continuous trading. Offering price improvement makes wholesalers more attractive to retail brokers by giving their clients better execution prices. However, price improvement reduces the wholesaler's revenues. By internalizing the order in continuous trading, wholesalers earn the quoted spread, particularly when they have the priority on an exchange as a DMM. However, executing orders at the quote without price improvement may cause retail brokers to route orders to other wholesalers offering better price improvements. Thus, wholesalers must balance the immediate profits from internalizing in continuous trading against the longer-term benefits of attracting and retaining order flow through price improvements in auctions.[5]

Consistent with wholesalers competing for retail orders, marketable orders executed in auctions receive higher execution quality (higher price improvement and lower trading costs) than orders executed in the continuous market. Consistent with wholesalers earning revenues to pay PFOF in continuous trades as opposed to auctions, Figure 1a decomposes trading costs and shows price improvement of 67% of quoted spreads and significantly lower market maker revenues for auctions than for continuous trades.[6] To examine how auctions interact with PFOF, we follow Ernst and Spatt (2023) to identify options on exchanges where the DMMs are wholesalers paying PFOF. We refer to these as PFOF exchanges, to auctions on PFOF exchanges as PFOF auctions, and to continuous trades on PFOF exchanges as PFOF continuous trades. Across all auctions, Figure 1b illustrates that PFOF auctions generate higher execution quality and lower MM revenues than non-PFOF auctions. Figure 1b shows that the difference in MM revenues between auctions and continuous trading is driven by the negative market making revenues for PFOF-exchange auctions. The differences in Figure 1 hold in regressions with fixed effects and controls for market conditions and trade characteristics. The larger spreads and market maker revenues suggest that PFOF wholesales earn revenue in continuous trading to pay PFOF.

PFOF wholesalers manage their execution quality on different dimensions to attract PFOF order flow. To avoid providing poor execution on individual trades, PFOF wholesalers provide more frequent price improvement in options with wide spreads. To dynamically avoid poor performance PFOF wholesalers increase their price improvement when their recent price improvement has been lower than average and lower than other wholesalers' recent price improvement. This increased price improvement is achieved by running more frequent auctions rather than offering more price improvement in each auction. PFOF wholesalers use auctions to avoid poor performance both on individual orders and across all orders.

The SEC's proposed equity Order Competition Rule imposes auction-like mechanisms for retail orders similar to those in the options market. The SEC

5 Appendix A2 illustrates these trade-offs in more detail.

6 Market maker revenues are calculated as the quoted spread net of hedging costs and any price improvement.

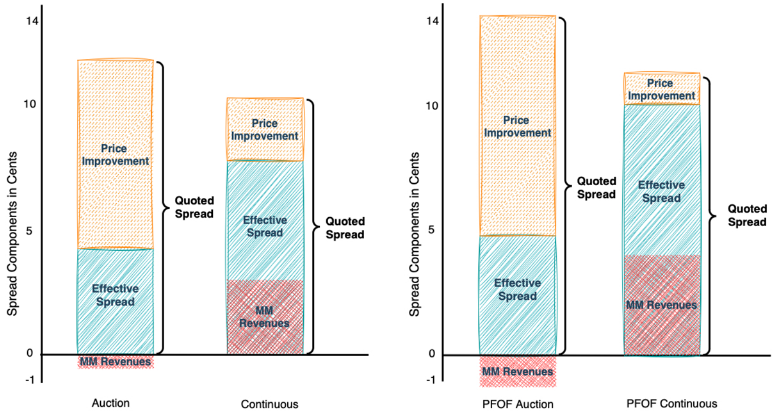

Figure 1
Components of quoted spreads
This figure illustrates the components of spreads for auctions and continuous (nonauction) trades in cents, as well as for PFOF auction and continuous trades.

claims its proposal would lead to better retail execution through increased competition among auction bidders. However, our analysis reveals that options auctions rarely feature multiple bidders, with less than 10% having more than one bidder at the winning price and most multiple bids occurring in minimum price improvement scenarios. Hence, despite options having wide spreads and high MM revenues, 90% of option auctions do not exhibit evidence of competition in terms of multiple bidders at nonminimal price improvement. Furthermore, in options the auction initiator, for example, the PFOF wholesaler, is required to bid, offering at least the minimum price improvement. Competition among PFOF wholesalers provides the incentive to initiate options auctions. In contrast, the SEC's equity auction proposal lacks any participation incentives. Overall, evidence from options auctions suggests that more than 90% of equity auctions could fail to attract multiple competitive bids.[7]

In addition to the frequency of price improvement, the size of price improvement is important to evaluate possible auction benefits. The SEC's order competition proposal estimates the benefits of equity auctions in terms of more aggressive auction bidding than wholesalers' current price improvement on internalized equity orders.[8] For the S&P 500 stocks we study, in its Table 7 the SEC suggests that bids may improve by 0.7 cents with auction

[7] Consistent with this, Ernst, Sun, and Spatt (2023) show that stock exchanges have low participation in their exchange retail liquidity programs.

[8] The SEC assumes that realized spreads (MM revenues) in the auctions would be more similar to those in the exchange limit order books, which are negative. However, the SEC fails to provide evidence that the timing and characteristics of retail orders are similar to those of exchange orders.

competition. Applying our 10% rate of multiple winning bids in options to the SEC's estimate of the benefits of auction competition yields an expected unconditional gain of 0.07 cents per auction over existing price improvement. For stocks, the SEC calculates that wholesalers offer average conditional price improvement of 1.47 cents 93.33% of the time, yielding an unconditional average of 1.37 cents.[9] If 90% of auctions fail to provide price improvement, the fraction of auctions without multiple competitive bids from the prior paragraph, then expected price improvement would fall by 1.27 cents in auctions relative to the current PFOF price improvement. This is substantially larger than 0.07 cents of increased price improvement the other 10% of the time.[10] The evidence from options auctions contrasts sharply with the SEC's optimistic estimates, suggesting that the proposed equity auction model may result in more significant costs than benefits.[11]

Bryzgalova, Pavlova, and Sikorskaya (2022) use auctions and small trades as proxies for retail trading, estimating that retail trading may account for over 60% of total options volume, with more than 95% of retail options orders purchased by wholesalers. Our analysis finds that PFOF DMMs with wholesaler arms hold 14.75% of auction volumes and offer frequent price improvements, suggesting that these auctions are predominantly retail. Given that PFOF wholesalers earn lower revenues in auctions, they are incentivized to route orders to exchanges where they have DMM priority, leading to 19.41% of PFOF DMM trades occurring in continuous trading.[12] Together with auctions, this accounts for nearly 40% of trading volume, indicating that retail orders also execute in non-PFOF continuous trading.[13] For researchers aiming to capture retail trading activity, starting with PFOF auctions is advisable, with a broader analysis including PFOF continuous trading and non-PFOF auctions to enhance robustness. Because auctions and PFOF exchanges are publicly available, studying retail trading is easier in options than the underlying stocks.

9 Dyhrberg, Shkilko, and Werner (2022) estimate that retail wholesalers provide higher price improvement in S&P 500 stocks and Battalio and Jennings (2023) find large price improvement for National Market Systems stocks.

10 Requiring only a single bid at nonminimal price improvement yields roughly 55% of auctions with price improvement. Using this in place of 10% in the prior calculations implies that expected additional price improvement is 0.39 cents and lost price improvement is 0.62 cents. In addition to forgone price improvement, auctions failing to attract bids will likely receive worse prices than the best price at the time of auction. The SEC estimates suggest that 4.6% of the time the quote would move against the retail auction initiator by 1 cent (see pages 286-293 of https://www.sec.gov/files/rules/proposed/2022/34-96495.pdf) although, the SEC notes that the frequency of adverse price movements may be larger for pretrade auction messages than their estimate using posttrade execution messages. Together, these imply a 0.046 cent cost per failed auction. Battalio and Jennings (2023) estimate substantially higher fail rates and adverse price movements.

11 The options market differs from the equity market in several ways, particularly in terms of market structure and spreads, with options exhibiting wider quoted spreads (10.45 cents compared to 1 cent for S&P 500 stocks) and mandatory on-exchange execution for all trades. Further differences between the equity and options market structures are discussed in Appendix A3. Whether these differences would result in auctions functioning better in equities requires further study.

12 Exchange market shares are roughly 8% higher when the DMM pays significant PFOF, consistent with wholesalers routing more orders to their affiliated DMMs.

13 A recent NYSE report suggests that retail trading in equity option ranges from 45% to 48%.

Overall, auctions provide large price improvements and have lower trading costs and market maker revenues. PFOF auctions further improve auction execution quality by offering lower trading costs, higher price improvements, and lower MM revenues compared to non-PFOF auctions. PFOF DMMs initiate more auctions when their execution quality is worse than their competitors. These results suggest robust competition among PFOF wholesalers in auctions. In contrast, nonauction continuous competition appears less robust, characterized by wider spreads and higher MM revenues.

Past research shows that competition between markets leads to lower execution costs in options. Neal (1987) studies options market competition in the late '70s and early '80s and shows that options listed on multiple exchanges have lower bid ask spreads. Mayhew (2002) studies similar questions in a long time-series between 1986 and 1997 with a number of regulatory changes including the abolition of the allocation plan that restricted multiple listings. He shows that options listed on multiple exchanges have narrower quoted spreads. He also shows that designated markets makers tend to offer narrower quoted spreads than open outcry markets. de Fontnouvelle, Fishe, and Harris (2003) study a period of intensive competition for options listings starting in 1999. They also show that listing an option on multiple exchanges leads to lower execution costs and that this is best explained by intermarket competition. Battalio, Hatch, and Jennings (2004) study the introduction of electronic linkages between option markets. They find that effective spreads are narrower and that investors are more likely to trade at the best price when markets are electronically linked to form a national market system similar to that of the equities market.

In options, exchanges and wholesalers pay brokers for orders. Chordia and Subrahmanyam (1995) suggests that PFOF exists because the minimum tick size is larger than the marginal costs of market making. Battalio and Holden (2001) show that screening can lead to PFOF without discrete prices. Parlour and Rajan (2003) extends these models to show that limit orders can lead to PFOF with continuous prices even without asymmetric information.

More recently, Battalio, Shkilko, and Van Ness (2016) study execution cost differences between maker taker and PFOF exchanges. While focusing on the fee models of option exchanges, they note the existence of price-improving auctions and DMM preferencing. They find that the inclusion of fees can explain some of the routing decisions of brokers to venues that pay marketing fees to order flow providers, called PFOF venues. PFOF for exchanges focus on the payments by exchanges while PFOF wholesalers focus on the payments by wholesalers who make the routing decisions. These types of PFOF can be related, as exchange PFOF can be used to attract PFOF wholesaler order flow. In addition, auctions are a way for PFOF exchanges not currently offering the best price to execute orders as opposed to routing the orders to other exchanges. Bryzgalova, Pavlova, and Sikorskaya (2022) highlight the rise of the three largest wholesalers, and that retail traders in options lose money on average.

Focusing on PFOF, Ernst and Spatt (2023) examine the choice between options and stocks for retail investors. They document that brokers have incentives to encourage retail investors to trade options that generate large PFOF from wholesalers. Prior to our results on PFOF DMMs, Ernst and Spatt (2023) examine how price improvement varies with the five-contract cutoff and tick size, neither of which we do. Finally, they examine how quoted spreads vary with PFOF DMM assignments, similar to one column of our Table 6. Consistent with our results Ernst et al. (2024) demonstrates in a recent paper focusing on equity markets that retail brokers base their order routing decisions (at least in part) on retail execution quality statistics.

The effect of market makers receiving preferential priority when matching competing market makers' quoted prices played a prominent role in analysis of competition on Nasdaq when it was a dealer market (e.g., Godek 1996; Dutta and Madhavan 1997). Such price matching and preferencing can dull the incentives for market makers to offer more competitive prices, thus increasing trading costs. If desirable trades are preferenced by PFOF DMMs, for example, for adverse selection or inventory cost reasons, then competition is further inhibited (Kandel and Marx 1997). Our results are consistent with PFOF DMMs routing more profitable orders to themselves in continuous trading, which may hinder competition.

1. Option Market Liquidity, Payment for Order Flow, and DMMs

In equity markets, orders can execute on-exchange or off-exchange with broker-dealers, wholesalers, or on alternative trading systems. In options markets, all trades must execute on a National Market System exchange if they are to be cleared by the SEC regulated Options Clearing Corporation. There are 16 NMS option exchanges, operated by five exchange groups (CBOE, ICE, MIAX, Nasdaq, and TMX). Andersen et al. (2021) present descriptive statistics for these exchanges. We focus on two trade types reported in the Options Price Reporting Authority (OPRA) data feed: (1) auto-electronic (code I) and; (2) electronic auctions (code a).[14] These two trade types make up approximately 77% and 23%, respectively of all single-leg trading in our sample. Collectively, they account for 96% of all single-leg trades. Auto-electronic trades execute in continuous trading.

Options market structure differs from equity market structure on a number of dimensions. First, all trades in exchange-listed options must occur on exchanges. Second, retail price improvement over the best displayed prices occurs in auctions on exchanges. Third, many options exchanges utilize secondary priority rules that favor designated market makers in nonauction trades in continuous trading. We refer to exchanges with preferential DMM

[14] We are grateful to Citadel Securities for providing OPRA data and helpful conversations.

priority rules as DMMP (DMM-priority) exchanges. Fourth, the wholesalers utilizing PFOF are also DMMs, which, subject to best execution rules, allows them to route PFOF orders to exchanges where an affiliated DMM has preferential priority.[15] Following Ernst and Spatt (2023), we identify options that have PFOF DMMs versus non-PFOF DMMs on different exchanges.[16] We utilize this variation to examine how PFOF relates to order routing, auctions, and trading costs.

DMMP exchanges appointing DMMs with allocation priorities have operational differences from other exchanges.[17] In markets without DMMs, orders are executed in a limit order book based on a price-time priority rule, where orders are filled based on their price and the time they were received. In contrast, options markets with DMMs use a combination of pro-rata allocation and DMM priority rules.[18] DMM priority rules allow the DMM to have priority in the execution of orders at the best available price. DMMs have priority for the entire order if it is for five-contracts or less. If the order is for more than five-contracts, DMMs are usually allocated between at least 40% and 50% of the order.[19]

In electronic auctions, bidders must improve upon or, in some cases, match the best available price in continuous trading. Price improvement also exists in continuous trading in the form of hidden orders within the posted bid-ask spread. Auctions include a number of features that provide advantages to participants that bring an order to the auction. For instance, if a wholesaler brings an order to an auction, they are guaranteed at least 40% or 50% of the order if they are quoting at the best price in the auction.[20] This is similar to the allocation rules used in continuous trading with DMMs for orders for greater than five-contracts. Wholesalers can also auto-match the best prices submitted by other auction participants.[21] Auto-matching allows wholesalers guaranteed participation in the auction without competing on price.

[15] The DMMs can completely internalize incoming orders for five or fewer contracts and receive preferential allocations of at least 30% and up to 50% of the incoming order for greater than five-contracts. The DMM must be quoting at the best price to receive these preferential allocations. Retail customers typically have priority over DMM orders.

[16] We identify option DMM assignments for the nine exchanges for which publicly available symbol DMM assignment is available. DMM assignments are an imperfect proxy for PFOF wholesalers' routing decisions as routing is determined by the relative quotes of other market makers as well as differences in exchange fees.

[17] Some markets appoint DMMs without priority.

[18] These exchanges generally preference customer orders first.

[19] See CBOE - Rules pages 252–254 for an overview of limit order book priority rules.

[20] Wholesalers are guaranteed 50% if there is one other bidder in the auction and 40% if there is more than one additional bidder.

[21] See CBOE Crossing Order Type for a description of guaranteed allocations and auto-matching rules. Other exchange groups have similar features and Ernst and Spatt (2023) note that these features are the same on Nasdaq PHLX.

1.1. Data and descriptive statistics

The data are from OPRA and include exchange, trade price, quoted spread, contract size, option underlying, strike, call or put, and other data. We focus on single-leg equity options with S&P 500 stocks as the underlying. We match OPRA to the underlying stock data using the Trade and Quotation (TAQ) database. We match option trades with the underlying quote 1 millisecond before the option trade. This method ensures that we are using stock prices, quotes, and volumes immediately before the option trade. We use the methods outlined in Holden and Jacobsen (2014) to process TAQ. Andersen et al. (2021) provide a descriptive overview of the OPRA data. We further augment our data set by matching to OptionMetrics, which provides us with closing option quotes for all days in our sample.

Our sample period is August through December of 2020. This period is after the market dislocations of March and April of 2020 and the floor closure and re-opening periods. This provides a recent sample period without major market movements to examine normal and recent option market trading. We present all results for the full sample of approximately 79 million trades and in our regression setting we also present results for a subset of approximately 26 million matched trades. Our matched sample consists of continuous (nonauction) trades executed within 5 seconds of a given auction trade for the identical underlying. The matched sample increases the likelihood that we are comparing orders during similar market conditions. We match trades executed by PFOF DMMs to non-PFOF DMM trades based on the following trade characteristics: i) underlying symbol, ii) trade type (continuous trades versus auction), iii) type of option (call versus put), iv) date on which the trade executed, v) prevailing option midpoint, vi) trade size measured in contracts, and vii) delta of the option. We start with the first four variables and require an identical match. We then use propensity score matching to match on the option midpoint, trade size, and option delta. Sample statistics for the treated and matched sample are presented in Appendix Table A1.

Each trade in our sample is matched to the prevailing option midpoint computed from the best bid and ask prices across option markets. Using the Lee and Ready (1991) tick test, we sign all trades as either buyer or seller initiated.[22] Defining D as the signed trade direction, we compute (half) dollar effective spreads as follows:

$$Effective\ Spread = D \times (p - m), \tag{1}$$

where p is option price and m is the prevailing midpoint. Trades taking place at a price better than the quoted prices receive price improvement. For expositional ease, we often omit half when referring to the quoted and effective

[22] The OPRA data does not include trade initiator. For price improvement greater than half of the spread, the tick test will mismark buys as sell and vice versa. This biases measurement of the effective spread and the ratio of the effective spread to the quoted spread (EQ).

Table 1
Summary statistics

	Unit	Mean	St.Dev	Percentiles 5%	25%	50%	75%	95%
Quoted Spread	Cents	10.45	2.18	8.05	8.96	9.71	11.68	14.95
Effective Spread	Cents	7.02	1.45	5.35	5.96	6.58	8.00	9.58
Price Improvement	Cents	3.43	0.77	2.63	2.95	3.16	3.67	5.00
Market Maker Revenues	Cents	2.20	1.39	0.44	1.35	2.16	2.94	4.28
Trades	1,000s/day	744.28	147.82	540.10	635.02	726.76	837.72	1,016.64
Number of auctions	1,000s/day	168.39	32.26	115.60	146.28	167.07	188.77	226.93
Trade size	Contracts	4.50	17.94	1.00	1.00	1.00	3.00	15.00
Trade size	1,000s $	2.45	18.01	0.04	0.15	0.46	1.55	8.79
Dollar volume	Billions $/day	1.82	0.56	1.14	1.39	1.75	2.08	3.08
Options traded	1,000s/day	4.99	0.44	4.37	4.71	4.96	5.24	5.69
Option Price	$	8.66	1.64	6.43	7.45	8.56	9.42	11.72
Call Volume	%	75.48	5.52	66.05	72.29	76.29	79.31	82.59
Put Volume	%	24.52	5.52	17.41	20.69	23.71	27.71	33.95
Days-to-expiration	Days	25.22	3.09	20.27	23.28	24.94	27.11	30.24
$\mid Delta \mid$		0.35	0.02	0.31	0.34	0.36	0.37	0.38
Underlying Midpoint	$	142.00	6.40	133.04	136.83	140.37	148.08	152.31
Market capitalization	$ Billion	58.43	150.91	4.56	12.40	23.18	52.00	203.48

This table presents sample descriptive statistics computed from daily trade-weighted averages. *Quoted spread* is half the difference between option ask and bid prices prevailing at the time of trade. *Effective spread* is the difference between option price and midpoint, times trade direction. *Price improvement* is the difference between option quoted spread and effective spread. *Market capitalization* is price times shares outstanding from the end of the previous month. *Option price* is quoted per unit of the underlying stock. *Underlying midpoint* is the prevailing stock midpoint at the time of option trade. *Call* (*put*) *volume* is daily call (put) traded volume as a percentage of total traded volume. *Market maker revenues* is the difference between effective spread and the sum of initial and dynamic hedge cost components.

spread. The difference between the half quoted and effective spreads is price improvement, which equals the difference between the trade price and relevant best quote, the ask for a buy and the bid for a sell:

$$Price\ Improvement = \mathrm{QS} - \mathrm{ES}. \tag{2}$$

Table 1 reports summary statistics calculated as daily trade-weighted averages. Quoted bid-ask half spreads are wide in options markets at slightly more than 10 cents and considerably wider than the underlying quoted spreads. Trade prices are low making quoted spread in relative terms even wider than equities at 1.21% of the midpoint. Spreads in equity markets, and particularly in S&P 500 stocks, are typically narrower. Hagströmer (2021) reports quoted bid-ask spreads in U.S. equities of roughly 3.55 basis points. Both in absolute and relative terms, the quoted bid-ask spread in the options market is wide. Muravyev and Pearson (2020) presents evidence that the quoted spread may overestimate actual liquidity costs for informed traders. Our results suggests that the quoted bid-ask spread may also overestimate execution costs for uninformed traders due to price improvement available in continuous trading and in auctions.

The effective spread is what an investor pays when demanding liquidity after price improvement. The effective spread for option trades is 7.02 cents, meaning that prices improve on average by 3.43 cents, or 0.79 % of the option price. We calculate a revenue measure that takes into account the immediate (Cho and Engle 1999) and dynamic daily hedge costs (Leland 1985) per option. The market maker revenues that take hedge costs into consideration are still large at 2.2 cents and 0.25% of the option price.

On average, there are more than 744 thousand trades and 168 thousand auctions per day. Slightly fewer than 5,000 different options trade on an average day with an average price of $8.66. Trades are small, on average, at 4.50 contracts for $2,450. Traded options have absolute value deltas of 0.35, suggesting that more out-of-the-money than in-the-money options are traded. Calls are traded 75% of the time and the average days-to-expiration of traded options is 25.

Similar to Bryzgalova, Pavlova, and Sikorskaya (2022), we compile data from SEC Rule 606 reports on PFOF paid to the largest retail brokers by option wholesalers. In Table 2, we document 15 wholesalers that pay 160 million dollars of PFOF per month over our 5-month sample. Citadel is the largest wholesaler and pays roughly 72 million dollars per month, representing more than 45% of the total PFOF paid in options. The next three largest wholesalers, Susquehanna, Wolverine, and Dash, make up roughly an additional 47% of the total PFOF paid. Together these four wholesalers comprise more than 92% of PFOF paid. Rule 606 data also reports the PFOF paid per contract in cents, ranging from an average of 49.84 to 33.23 cents. The four largest wholesalers pay, on average, more per contract than do smaller wholesalers, perhaps because they purchase option orders that are more expensive or harder to trade. The wholesalers that pay the most PFOF also purchase the most contracts. When an auction is broken up by a noninitiator, the break-up fee paid by the noninitiating winner of the auction can range from 50 cents to 105 cents on CBOE. This is more than the PFOF paid to acquire the order and 10 times more than the initiator pays when they win the auction.

Panel D of Table 2 reports the DMMs that are appointed on the nine DMMP exchanges for which we could find publicly available underlying DMM assignments. DMMP exchanges allow DMM priority in continuous trading. We find that the wholesalers that pay the most PFOF also have the most underlying assignments. The top-four PFOF-paying wholesalers have affiliated market makers with more than 50% of DMM appointments. Citadel has at least one DMM appointment in 477 S&P 500 underlyings and 27% of the total appointments by option series. We also calculate the auction market share by DMMs and the average price improvement per auction. The frequency of auctions is roughly correlated with the percentage of underlying assignments and total PFOF paid. The two notable exceptions are Susquehanna and Two Sigma, which have higher auction market shares than underlying assignments. Per trade price improvement is higher in the big four PFOF-paying firms than in the smaller PFOF-paying firms. The outlier is Dash, with price improvement of only 0.64 cents.

Table 2
Wholesaler summary

A: Market orders and marketable limit orders

DMM	PFOF ($ M)	PFOF (%)	PFOF (cents) / 100 Contracts	Contracts Purchased (M.$)	Contracts Purchased (%)
Citadel	33.01	45.64	47.74	62.92	44.61
Susquehanna	24.04	33.24	50.37	41.31	29.26
Wolverine	6.05	8.38	45.96	11.92	8.44
Dash	5.55	7.72	47.26	12.58	8.95
Morgan	2.46	3.36	39.86	4.88	3.43
WEX	0.25	0.36	31.66	0.79	0.58
Group One	0.60	0.85	14.77	5.95	4.23
Two Sigma	0.29	0.39	47.85	0.60	0.42
Matrix	0.04	0.05	31.67	0.11	0.07
Citigroup	0.04	0.06	38.57	0.12	0.09
Belvedere	0.00	0.00	0.00	0.00	0.00
GTS	0.00	0.00	0.00	0.00	0.00
Goldman	0.00	0.00	0.00	0.00	0.00
Merrill	0.00	0.00	0.00	0.00	0.00
No Data	0.00	0.00	0.00	0.00	0.00
XR	0.00	0.00	0.00	0.00	0.00

B: Nonmarketable limit orders

DMM	PFOF ($ M)	PFOF (%)	PFOF (cents) / 100 Contracts	Contracts Purchased (M.$)	Contracts Purchased (%)
Citadel	31.10	46.34	50.93	54.50	45.44
Susquehanna	18.15	27.02	49.79	32.13	26.76
Wolverine	8.07	12.03	47.46	14.64	12.20
Dash	4.63	6.91	46.80	9.67	8.07
Morgan	2.74	4.04	39.27	5.02	4.16
WEX	1.80	2.68	58.44	2.87	2.39
Group One	0.45	0.67	61.23	0.73	0.61
Two Sigma	0.15	0.22	47.56	0.31	0.26
Matrix	0.09	0.12	43.10	0.19	0.15
Citigroup	0.04	0.06	42.58	0.09	0.08
Belvedere	0.00	0.00	0.00	0.00	0.00
GTS	0.00	0.00	0.00	0.00	0.00
Goldman	0.00	0.00	0.00	0.00	0.00
Merrill	0.00	0.00	0.00	0.00	0.00
No Data	0.00	0.00	0.00	0.00	0.00
XR	0.00	0.00	0.00	0.00	0.00

C: Other orders

DMM	PFOF ($ M)	PFOF (%)	PFOF (cents) / 100 Contracts	Contracts Purchased (M.$)	Contracts Purchased (%)
Citadel	8.32	41.14	46.55	21.26	43.46
Susquehanna	4.99	24.72	48.84	11.45	23.42
Wolverine	1.30	6.40	51.01	2.95	6.02
Dash	3.60	17.77	40.38	8.58	17.52
Morgan	1.35	6.70	39.81	3.16	6.48
WEX	0.07	0.34	28.39	0.12	0.25
Group One	0.53	2.64	42.16	1.27	2.59
Two Sigma	0.01	0.04	47.61	0.01	0.03
Matrix	0.06	0.26	38.95	0.11	0.21
Citigroup	0.05	0.24	40.49	0.10	0.22
Belvedere	0.00	0.00	0.00	0.00	0.00
GTS	0.00	0.00	0.00	0.00	0.00
Goldman	0.00	0.00	0.00	0.00	0.00
Merrill	0.00	0.00	0.00	0.00	0.00
No Data	0.00	0.00	0.00	0.00	0.00
XR	0.00	0.00	0.00	0.00	0.00

(Continued)

Table 2
(Continued)

Panel D: Exchange data

						Auctions	
DMM	Exchanges	Underlying (#)	Underlying (%)	Options (#)	Options (%)	Freq. (%)	PImpr. (cents)
Citadel	2.23	477	25.65	414,671	27.78	25.92	4.02
Susquehanna	1.60	430	18.40	282,484	18.92	24.18	5.29
Wolverine	0.87	325	9.96	83,283	5.58	9.45	4.90
Dash	0.19	91	2.21	58,169	3.90	1.68	0.64
Morgan	0.66	242	7.55	80,945	5.42	8.45	3.08
WEX	0.00	0	0.00	0.00	0.00		
Group One	0.17	83	1.98	22,897	1.53	0.97	3.59
Two Sigma	1.00	355	11.53	257,651	17.26	15.07	2.48
Matrix	0.00	0	0.00	0.00	0.00		
Citigroup	0.28	139	3.24	13,898	0.93	0.55	3.53
Belvedere	0.08	39	0.90	9,287	0.62	1.16	2.50
GTS	0.40	171	4.55	77,838	5.21	4.72	4.29
Goldman	0.36	175	4.14	63,320	4.24	0.30	1.32
Merrill	0.02	9	0.21	1,811	0.12	0.00	0.41
XR	0.39	195	4.49	81,997	5.49	7.54	2.71

Panels A to C present payment for order flow paid by wholesalers from Rule 606 filings for the largest brokers. The last column presents contracts purchased by the wholesaler, expressed as a percent of contracts purchased by all wholesalers. Panel D presents DMM assignments. Column 1 of panel D shows the average number of exchanges a given market maker is a DMM for an underlying. Column 2 displays the count of unique symbol assignments, while column 3 presents the distribution of symbol assignments across all exchanges. Columns 4 and 5 provide analogous information to the previous two columns but specifically for option assignment. Columns 6 and 7 display the *auction frequency* and average *price improvement*.

In prior literature, Battalio, Shkilko, and Van Ness (2016) focuses on the business models of exchange. Some exchanges pay explicitly for order flow while others pay for liquidity supply in the form of market maker rebates. Table 3 reports exchange volume statistics and fee and market model information. Some exchanges have hybrid (continuous trading and floor) features, such as ARCA, and others have different fee models and priorities for different options and market phases. Exchange classification is done based on the predominant features using publicly available information. Nasdaq operates the three highest volume exchanges, NOM, GEMX, and PHLX, with 14.61, 11.91, and 11.44 of trading volume. NOM and GEMX use the maker taker fee model and PHLX uses the PFOF exchange fee model. Both GEMX and PHLX exchanges include auctions. We add information on the preferencing models of the exchange. Exchanges that grant DMMs and other market makers priority over other participants in continuous trading are classified as DMMP exchanges. While GEMX and PHLX have different exchange fee models, they are both DMMP exchanges and NOM is a non-DMMP and maker-taker-fee exchange. Roughly 54% of trading in our sample is on a DMMP exchange. Only five exchanges do not have auctions: ARCA, NOM, BATS, Pearl, and C2.

In Table 4, we report statistics on quoted and effective spreads, price improvement, and EQ for all exchanges categorized by continuous trading and auctions. In continuous trading, quoted spreads range from a low of 6.9 on

Table 3
Exchange summary

		Volume (%)					
Exchange	Group	All	LOB	Auctions	Preferencing	Model	Auctions
GEMX	Nasdaq	11.91	11.68	0.23	DMMP	MT	Yes
PHLX	Nasdaq	11.44	2.18	9.27	DMMP	PFOF	Yes
ARCA	ICE	10.91	10.91		DMMP	PFOF	No
CBOE	CBOE	7.41	2.63	4.78	DMMP	PFOF	Yes
MIAX	MIAMI	4.80	1.42	3.37	DMMP	PFOF	Yes
AMEX	ICE	4.62	2.31	2.31	DMMP	PFOF	Yes
MRX	Nasdaq	1.66	0.34	1.32	DMMP	MT	Yes
ISE	Nasdaq	0.70	0.49	0.21	DMMP	PFOF	Yes
BX	Nasdaq	0.53	0.52	0.00	DMMP	MT	Yes
NOM	Nasdaq	14.61	14.61		Non-DMMP	MT	No
BATS	CBOE	10.22	10.22		Non-DMMP	MT	No
EMERALD	MIAMI	9.28	9.28	0.00	Non-DMMP	MT	Yes
PEARL	MIAMI	4.06	4.06		Non-DMMP	MT	No
BOX	TMX	3.30	2.26	1.04	Non-DMMP	MT	Yes
EDGX	CBOE	3.19	2.65	0.54	Non-DMMP	MT	Yes
CBOE C2	CBOE	1.36	1.36		Non-DMMP	MT	No

This table presents statistics on option exchanges. DMMP denotes that the given exchange uses designated market maker preferencing. PFOF (MT) denotes that the exchange uses payment for orderflow (maker taker pricing) fee model.

CBOE C2 to a high of 19.65 on MRX. Price improvement is low in continuous trading, and ranges from 5.27 cents on BATS to 0.10 on AMEX.[23] A notable finding is that price improvement in continuous trading is almost exclusively higher on non-DMMP exchanges. For auctions, the effective spread is lowest on EDGX and highest on ISE, where price improvement ranges from 0.99 on GEMX to 9.69 on the CBOE. Only one DMMP exchange does not also have an auction facility while only three of seven non-DMMP exchanges have auctions. Quoted spreads are recorded at the time of trade. Because trades may occur on different exchanges for options with different liquidity or in different market conditions, average trade-time quoted spreads across exchanges need not reflect the quality of execution provided by exchanges. Moreover, Anand, Hua, and McCormick (2016) show that differences in exchange model (make-take versus PFOF) can lead to systematic differences in the characteristics of order types routed to these exchanges, which can, at least in part, explain differences in execution quality across exchanges.

Option exchanges and brokers often use the ratio of the effective spread to the quoted spread to compare execution quality. The EQ in continuous trading is often double that in auctions, and almost all non-DMMP exchanges

[23] NOM is the only exchange that operates solely with continuous trading, offering order prices within the symbol tick, which can lead to price improvement. Our measured price improvement on other exchanges may result from OPRA quotes not reflecting aggressively priced non marketable limit orders that execute almost immediately. Options exchanges' quote mitigation policies can lead exchanges to report transactions within the OPRA spread without updating OPRA.

Table 4
Option exchanges and execution costs

	Continuous Trading				Auctions			
Exchange	*Quoted Spread*	*Effective Spread*	*Price Improvement*	*EQ*	Quoted Spread	*Effective Spread*	*Price Improvement*	*EQ*
GEMX	9.84	8.44	1.40	0.91	8.00	7.01	0.99	0.84
PHLX	13.42	12.00	1.42	0.93	11.41	3.84	7.57	0.50
ARCA	10.37	10.08	0.30	0.98				
CBOE	9.80	7.64	2.16	0.88	14.45	4.76	9.69	0.43
MIAX	6.94	6.76	0.18	0.98	12.20	4.13	8.06	0.49
AMEX	9.12	9.02	0.10	0.99	10.18	3.06	7.12	0.50
MRX	19.65	19.44	0.20	0.98	13.42	6.12	7.30	0.59
ISE	14.29	13.31	0.97	0.96	10.69	7.38	3.31	0.81
BX	12.85	11.91	0.94	0.95	5.55	3.49	2.06	0.75
NOM	9.25	7.01	2.24	0.82				
BATS	11.33	6.07	5.27	0.66				
EMERALD	10.82	8.80	2.01	0.90	8.38	4.05	4.33	0.53
PEARL	10.66	7.10	3.55	0.81				
BOX	13.71	8.68	5.04	0.77	14.34	6.08	8.26	0.62
EDGX	11.48	8.45	3.02	0.87	6.93	2.75	4.18	0.58
CBOE C2	6.90	4.45	2.46	0.83				

This table presents execution cost variables across option exchanges. *Quoted spread* is half the difference of option ask and bid prices prevailing at the time of trade. *Effective spread* is the difference between option price and midpoint, times trade direction. *Price improvement* is the difference between option quoted spread and effective spread. *EQ* is the ratio of effective and quoted spread. All variables except *EQ* are in cents. All statistics are trade-weighted averages.

during continuous trading have lower EQ ratios.[24] We explore explanations and implications in the following sections.

2. Investor Costs, Best Execution, and Market Maker Revenues

In equity markets, the execution costs for retail investors are small, in some cases less than a half-penny. In options markets, the costs of demanding liquidity are quite high and can exceed 10 cents, or more than 1.5% of the price of the option. This means that an investor using market orders would have to generate returns of greater than 6% to break even on a round-trip trade. While overall costs can be high, PFOF might offer better executions than the market average. Quoted spreads measure the costs of demanding liquidity for trades that do not receive price improvement. Quoted spreads are also an important component of PFOF paid to brokers.[25] Wider quoted spreads make it easier for DMMs to offer price improvement and to generate positive revenues when trading with retail customers.

Brokers and DMMs to whom execution is delegated are required to ensure that orders are executed at the best prices. In the December 14th

[24] Note that a higher EQ relates to worse execution quality for a customer.

[25] Robinhood charges wholesalers for orders based on the quoted spread.

SEC Best Execution proposal, brokers would be required to ‘’…execute customers’ trades at the most favorable terms reasonably available under the circumstances.”[26] Because there is significant price improvement available in option markets, it is not sufficient to simply ensure that orders execute on the exchange with the best available price. Brokers, and the wholesalers to whom they route their orders, should take into consideration the price improvement available in continuous trading and in auctions. In continuous trading, hidden orders can be posted within the posted spread providing price improvement to the order that executes against that order. Price improvement can also be provided directly in price improving auctions.

Figure 1a visualizes the individual components of the quoted spread by auction and continuous trading. Figure 1b visualizes the individual components of the quoted spread for PFOF auction and continuous trades.

Auction quoted spreads and price improvement are larger than those for continuous trading. Because the difference in price improvement is greater than for quoted spreads, auctions have narrower effective spreads. Auction quoted spreads are wider for PFOF and, despite the larger price improvement, PFOF auctions also have higher than average effective spreads. Effective spreads are widest for PFOF continuous trades. While PFOF auctions have negative MM revenues, continuous trades have large and positive revenues.

Table 5, panel A, reports average execution costs and statistics in auctions, for PFOF-paying DMMs, for non-PFOF-paying DMMs, and for the difference between them. Quoted spreads are 16.68% wider for auctions than for continuous trades at 11.75 and 10.07 cents, respectively. Auctions effective spreads are less than half of the quoted spread. The difference is driven by the large price improvement in auctions of 7.62 cents versus 2.2 cents in continuous trading. The EQ ratio is also roughly half in auctions, at 0.38, than in continuous trading, at 0.74.

For PFOF DMMs, the effective and quoted spreads are wider than for non-PFOF. The auction quoted spread is 4.07 cents wider for PFOF than for non-PFOF. The effective spread for PFOF is wider by 1.22 cents. This is driven by the 8.93 cents of price improvement offered by PFOF and only 6.09 of price improvement offered by non-PFOF. The EQ ratio for PFOF is slightly lower than the non-PFOF EQ ratio. The results show that PFOF bring orders to auctions with extremely wide quoted spreads and offer them considerable price improvement, but these orders still pay higher execution costs than non-PFOF.

Panel B reports the same statistics for continuous trading. Quoted spreads and effective spreads are wider for PFOF-paying DMMs. Effective spreads are 10.19 cents for PFOF DMMs and 7.17 for non-PFOF DMMs. In contrast to the auction results, price improvement is lower for PFOF than for non-PFOF. PFOF trades receive 0.98 cents of price improvement in continuous trading

[26] Page 6 of SEC Best Execution Rule proposal.

Table 5
Execution costs

A: Auctions

		All	PFOF	NPFOF	PFOF – NPFOF
Quoted Spread	Cents	11.75	13.62	9.56	4.07***
Effective Spread	Cents	4.12	4.69	3.47	1.22***
Price Improvement	Cents	7.62	8.93	6.09	2.84***
Trade Size	Contracts	5.14	5.21	5.07	0.14**
Trade Price	$	7.90	9.76	5.73	4.02***
Stock Midpoint	$	391.55	511.71	250.65	261.06***
EQ		0.38	0.37	0.38	–0.01***
Market Maker Revenues	Cents	−0.59	−1.38	0.34	–1.72***
Hedge Cost	Cents	4.66	6.01	3.07	2.95***

B: Continuous trading

		All	PFOF	NPFOF	PFOF – NPFOF
Quoted Spread	Cents	10.07	11.16	9.74	1.42***
Effective Spread	Cents	7.87	10.19	7.17	3.01***
Price Improvement	Cents	2.20	0.98	2.57	–1.59***
Trade Size	Contracts	4.33	4.16	4.38	–0.22***
Trade Price	$	8.88	10.44	8.42	2.03***
Stock Midpoint	$	379.57	483.90	348.24	135.66***
EQ		0.74	0.90	0.69	0.20***
Market Maker Revenues	Cents	3.01	4.07	2.69	1.38***
Hedge Cost	Cents	4.73	5.95	4.36	1.59***

This table presents average execution costs for trades that execute in auction (panel A) or continuous trading (panel B). *PFOF* denotes that the trade is executed at an exchange where the designated market maker pays significant payment for order flow and NPFOF if otherwise. *Quoted spread* is half the difference of option ask and bid prices prevailing at the time of trade. *Effective spread* is the difference between option price and midpoint, times trade direction. *Price improvement* is the difference between option quoted spread and effective spread. *EQ* is the ratio of effective and quote spread. *Market maker revenues* is the difference between effective spread and hedge cost. *Hedge cost* is the sum of initial and dynamic hedge cost components. Our sample period is the second half of 2020: August 2020 through December 2020. Spreads are winsorized at the 1% level on each tail. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

while non-PFOF trades receive roughly 2.57 cents of price improvement. This is driven mostly by trades that execute on non-DMMP exchanges where price improvement in continuous trading is higher. Dyhrberg, Shkilko, and Werner (2022) show in the equity market that price improvement in S&P 500 stocks is roughly 44% of the bid-ask spread. The effective spreads for PFOF trades are 42% larger than for non-PFOF trades in continuous trading.

2.1. Price improvement

The difference between the quoted spread and the effective spread is price improvement. Price improvement is higher in auctions by 5.4 cents. Price improvement is lower for PFOF continuous trades but higher for PFOF auctions. The results are similar for the matched sample.

The effective spread to quoted spread ratio is an often used measure of best execution in options markets. A higher EQ represents worse execution quality and a lower EQ represents better execution quality. The EQ ratio is bounded by 0 and 1.[27] For instance, an order with zero price improvement would have an EQ of 1. Similarly, a negative coefficient in our EQ regression suggests that execution quality is better because it has a lower effective spread relative to the quoted spread. Consistent with the previous evidence, we find that the EQ is lower in auctions than in continuous trading, considerably lower by 0.36. PFOF continuous trades have higher EQ ratios by 0.20 and lower ratios in auctions by 0.01. The results are similar in the matched sample.

2.2. Market maker costs and revenues

Options market makers earn revenues when they buy (sell) at lower (higher) prices than the cost of hedging their risk. Market makers pay for order flow and also incur fixed costs associated with the market data and technology required to provide quotes in 1,000,000+ options. Hence, market maker profits may be substantially lower than revenue estimates based on trading data.

2.2.1. Hedge costs. In equities, buying and selling occurs frequently throughout the trading day. This provides MMs with numerous opportunities to manage their inventories, meaning that MMs are unlikely to hold unwanted inventories for long periods of time. In options, thousands of individual options are written on a single underlying, often requiring MMs to hold unwanted positions for longer than equity MMs because trading can be thin or unbalanced in some options. Because of these issues, measuring MM costs net of adverse selection may not be the most appropriate measure of costs (Battalio, Shkilko, and Van Ness 2016). Following Leland (1985), Cho and Engle (1999), Engle and Neri (2010), and Christoffersen et al. (2018), we compute the costs of hedging the option trade.

In options markets, market makers hedge risk by purchasing the underlying. Hedging the underlying occurs at the time of the trade and periodically to account for changes in the underlying price. The initial hedge is calculated simply as the absolute value of the delta of the option times the number of contracts times 100 times the quoted spread in the underlying. As the price of the underlying moves, the initial hedge may not be adequate. If the price moves upwards, so does the delta of a call option. This means that the number of shares required to hedge the option will also increase. Leland (1985) models hedge costs associated with making markets in options. The delta of an option times the quoted spread in the underlying represents the initial hedge cost of an option from the perspective of a market maker. Dynamic hedge costs are proportional to the option vega, quoted spread of the underlying, and

[27] EQ is mismeasured for trades whose direction is incorrectly signed because price improvement is greater than half the quoted spread.

rebalancing frequency.[28] We follow Leland (1985) and calculate the expected dynamic hedge costs assuming a daily rebalancing frequency.

Descriptive statistics are reported in Table 5. We show that hedge costs are a large portion of the spread. In auctions, hedge costs are roughly 4.66 cents. PFOF hedge costs are double that of non-PFOF hedge costs, or about 2.95 cents higher. The hedge costs in continuous trading are lower than in auctions and the differences in costs between PFOF and non-PFOF are also lower. Average hedge costs in continuous trading are similar for PFOF and are higher for non-PFOF. On average, hedge costs in continuous trading are roughly half of effective spreads for PFOF and 61% for non-PFOF.

The assumption that each option traded is hedged directly in the underlying may be overly conservative. A more likely strategy involves hedging the portfolio and focusing on the market risk component, as the idiosyncratic risk component is likely to be small relative to the systematic component. Hedging market risk would entail hedging in S&P 500 futures or ETFs that are considerably more liquid than individual underlyings.

2.2.2. Market maker revenues. The bid-ask spread is the primary source of market maker revenues and PFOF. While the spread is wide in options markets, market makers have to engage in costly dynamic hedging strategies to reduce their exposure to risk. Battalio, Shkilko, and Van Ness (2016) note that the effective spread is not a good measure of market maker revenues in options. We subtract the hedge costs from the effective spread measure to compute market maker revenues. Our approach assumes that all risk is hedged in both auction and continuous trades. Market maker revenues are negative in auctions. This result is driven by the negative revenues of 1.38 cents for PFOF auctions, whereas non-PFOF have positive revenues of 0.34 cents.

When comparing continuous trades to auction trades, it is interesting to note that continuous trades generate large positive revenues. This suggests that DMMs might only break even or even lose money in auctions and recover losses in continuous trading. The average revenues are more than 3 cents per trade and more than 4 cents for PFOF and 2.69 cents for non-PFOF. Roughly 75% of trades occurring in continuous trading suggests that, even if PFOF DMMs lose money in auctions, the revenues from continuous trading may offset these losses and cover the fixed costs.

2.3. Regression results

The summary statistics suggest that execution costs are lower for non-PFOF than for PFOF trades. This could be driven by options that trade less often or are illiquid, or by differences in market conditions at the time of trade.

28 Leland (1985) theoretically derives the dynamic hedge cost as: $k\nu \frac{1}{\sqrt{2\pi\,\Delta t}}$, where k is the underlying transaction cost, ν is the option vega, and Δt is the rebalancing frequency.

To examine this, we estimate regressions where the dependent variables are reported in cents to provide evidence as to how market outcomes vary for auctions, PFOF-paying DMMs in continuous trading, auctions at exchanges in which a PFOF-paying DMM is appointed in continuous trading, and DMMP exchanges. We define dummy variables for PFOF for trades where the DMM pays significant PFOF, auction-for-auction trades, and DMMP for trades on exchanges that have preferential DMM priority rules. We run panel regressions with auction, PFOF, auction × PFOF, and DMMP dummy variables along with day and option underlying, for example, Apple, fixed effects as well as option and underlying characteristics. The PFOF coefficient measures the differences in trades on DMMP exchanges depending on whether the DMM pays PFOF. The sum of the coefficients on the PFOF and DMMP variables measures differences depending on whether the DMM pays PFOF relative to trades on all exchanges. The coefficient on the auction variable measures differences between non-PFOF auctions and nonauction continuous trades on non-DMMP exchanges. The sum of the coefficients on the PFOF, auction × PFOF, and DMMP variables measures differences in auctions trades depending on whether the DMM pays PFOF.

We present results for the full sample of approximately 79 million trades and for a subset of approximately 26 million matched trades. The underlying is an important component of option costs; with higher volatility and higher quoted spread, underlyings having wider quoted and effective option spreads. The regression also includes a buy/sell flag and a tick size indicator. Options with a wider tick have wider quoted and effective spreads. Buy trades have lower executions costs.

The control variables indirectly capture the costs of market making. We also include the absolute value of delta of the option and the gamma as well as the volatility of the underlying, similar to Engle and Neri (2010). Because we control for the components of hedge costs, the coefficients may be loosely interpreted as market maker revenues. In the last column, we report the result for MM revenues directly.

In Table 6, the results of five regressions are reported. The first two columns report execution costs; the first column reports the quoted spread and the second column the effective spread regression. The next two columns report best execution metrics, where the third column reports price improvement and the fourth column the EQ regression.[29] In the final column, we report MM revenues.

In panel A, we report the regression results for the full sample. In panel B, we report the results of a regression using our matched sample. Due to the large number of observations, most coefficients are significant and

[29] Ernst and Spatt (2023) examine how price improvement varies with the five-contract DMMP cutoff and tick size, neither of which we do. They also examine how quoted spreads vary with PFOF DMM assignments, similar to one column of our Table 6.

Table 6
Execution quality, auctions, and PFOF DMMs

A: Full sample

	Quoted Spread	*Effective Spread*	*Price Improvement*	*EQ*	*MM Rev.*
Auction	2.601***	–2.634***	5.236***	–0.410***	–2.607***
	(0.07)	(0.06)	(0.12)	(0.00)	(0.06)
PFOF	–0.561***	0.685***	–1.246***	0.067***	0.783***
	(0.07)	(0.03)	(0.08)	(0.00)	(0.04)
Auction × PFOF	1.829***	–1.587***	3.416***	–0.110***	–1.798***
	(0.14)	(0.07)	(0.20)	(0.00)	(0.09)
DMMP	–1.046***	0.754***	–1.800***	0.166***	0.812***
	(0.03)	(0.02)	(0.04)	(0.00)	(0.02)
|Delta|	30.298***	18.461***	11.836***	0.016***	6.454***
	(1.01)	(0.61)	(0.42)	(0.00)	(0.37)
Gamma	–13.370***	–8.135***	–5.235***	–0.175***	–2.442***
	(0.84)	(0.52)	(0.33)	(0.01)	(0.53)
Vega	19.177***	12.282***	6.895***	–0.008***	6.164***
	(0.68)	(0.43)	(0.26)	(0.00)	(0.42)
Underlying Volatility$_{t-1}$	14.917***	10.667***	4.251***	0.053***	
	(1.49)	(1.04)	(0.46)	(0.00)	
Underlying Quoted Spread	0.355***	0.220***	0.135***	0.000	
	(0.02)	(0.01)	(0.01)	(0.00)	
1/Option Midpoint	1.619***	0.945***	0.674***	0.009***	0.404***
	(0.06)	(0.04)	(0.03)	(0.00)	(0.03)
1/Underlying Midpoint	–72.203***	–40.373***	–31.830***	–0.097	–58.034***
	(21.52)	(13.59)	(8.06)	(0.26)	(14.34)
Underlying MCAP	4.324**	3.220***	1.104	0.007	1.833
	(1.66)	(1.05)	(0.62)	(0.01)	(1.24)
Trade size	–0.056***	0.010*	–0.066***	0.003***	0.010
	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)
Call	–1.192***	–0.947***	–0.245***	–0.008***	–0.898***
	(0.08)	(0.05)	(0.03)	(0.00)	(0.06)
Days-to-Expiry	1.885***	1.064***	0.821***	–0.000	0.886***
	(0.12)	(0.07)	(0.05)	(0.00)	(0.08)
Tick Size	0.549**	–0.018	0.567***	–0.016***	–0.013
	(0.26)	(0.16)	(0.11)	(0.00)	(0.16)
Buy	–0.121***	–0.202***	0.081***	–0.007***	–0.196***
	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)
R^2	0.453	0.398	0.180	0.239	0.174
NObs	78,893,354	78,893,354	78,893,354	78,893,354	78,893,354

(Continued)

we refrain from discussing statistical significance unless relevant. After controlling for economically important determinants of option liquidity, we find that the auction coefficient is higher for quoted spreads. The PFOF coefficient is slightly lower for quoted spreads, whereas PFOF auctions on DMMP exchanges have quoted spreads that are wider by 1.27 $(1.83-0.56)$ cents. In the matched sample, the auction coefficient is slightly lower for quoted spread than in the full sample. In general, the two samples present consistent evidence that auctions are run when spreads are wide and PFOF auctions are run when spreads are even wider. The coefficient on the PFOF variable is in the opposite direction of the unconditional results, perhaps because PFOF purchase and route orders in different options and underlyings than do non-PFOF.

To better understand investor execution costs, we estimate the same regression for effective spreads. The auction coefficient on effective spreads

Table 6
(Continued)

B: Matched sample

	Quoted Spread	*Effective Spread*	*Price Improvement*	*EQ*	*MM Rev.*
Auction	1.478***	–3.042***	4.520***	–0.339***	–3.046***
	(0.088)	(0.101)	(0.169)	(0.002)	(0.106)
PFOF	–1.351***	0.669***	–2.020***	0.174***	0.685***
	(0.086)	(0.049)	(0.085)	(0.002)	(0.050)
Auction × *PFOF*	1.799***	–0.845***	2.644***	–0.187***	–0.923***
	(0.113)	(0.052)	(0.125)	(0.002)	(0.055)
DMMP	–0.250***	0.547***	–0.797***	0.039***	0.547***
	(0.039)	(0.036)	(0.043)	(0.001)	(0.039)
|Delta|	33.947***	20.279***	13.668***	–0.010	5.532***
	(1.302)	(0.829)	(0.514)	(0.005)	(0.494)
Gamma	–17.279***	–10.679***	–6.600***	–0.058***	–2.007***
	(1.373)	(0.831)	(0.571)	(0.009)	(0.738)
Vega	17.581***	12.069***	5.511***	–0.003***	6.332***
	(0.669)	(0.437)	(0.249)	(0.001)	(0.442)
Underlying Volatility$_{t-1}$	14.688***	9.491***	5.197***	0.023***	
	(1.662)	(1.127)	(0.554)	(0.004)	
Underlying Quoted Spread	0.332***	0.201***	0.131***	–0.000	
	(0.020)	(0.012)	(0.008)	(0.000)	
1/Option Midpoint	1.787***	1.049***	0.738***	0.010***	0.411***
	(0.079)	(0.050)	(0.032)	(0.001)	(0.038)
1/Underlying Midpoint	–107.941***	–34.856*	–73.085***	–0.086	–53.343***
	(28.614)	(17.096)	(12.122)	(0.425)	(16.270)
Underlying MCAP	4.195	4.157***	0.038	0.003	3.036*
	(2.184)	(1.334)	(0.892)	(0.024)	(1.413)
Trade size	–0.130***	–0.003	–0.127***	0.006***	0.031***
	(0.015)	(0.008)	(0.010)	(0.000)	(0.008)
Call	–1.400***	–1.067***	–0.333***	0.005***	–1.098***
	(0.125)	(0.085)	(0.046)	(0.001)	(0.103)
Days-to-Expiry	2.105***	1.003***	1.101***	–0.006***	0.915***
	(0.156)	(0.095)	(0.065)	(0.001)	(0.101)
Tick Size	1.412***	1.224***	0.188	–0.009***	1.181***
	(0.331)	(0.210)	(0.128)	(0.002)	(0.206)
Buy	0.015	–0.114***	0.129***	–0.006***	–0.104***
	(0.021)	(0.018)	(0.014)	(0.000)	(0.017)
R^2	0.445	0.389	0.203	0.318	0.122
NObs	25,881,586	25,881,586	25,881,586	25,881,586	25,881,586

This table presents regression results for execution quality. *PFOF* is an indicator variable that equals one if the trade is executed at an exchange where the designated market maker pays significant payment for order flow, and zero otherwise. *Auction* is an indicator variable that equals one if the trade is executed at an auction, and zero otherwise. All dependent variables are defined in Table A2. Our sample period is the second half of 2020: August 2020 through December 2020. All specifications include underlying and day fixed effects. Spreads are winsorized at the 1% level on each tail. Standard errors are double-clustered at the underlying and day level and are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

is lower by 2.6 cents. The coefficient for PFOF is higher by 1.44 cents (0.69 + 0.75 cents). The PFOF auction coefficient, however, is lower by 0.90 cents. This coefficient is in the opposite direction of the unconditional results. This is likely explained by PFOF wholesalers routing orders in less liquid options and underlyings to themselves in auctions. For the matched sample, the coefficient on PFOF becomes smaller and PFOF auctions have lower effective spreads of only 0.6 cents.

The regressions also capture execution costs on DMMP exchanges. Because DMMP exchanges allow participants to direct order flow to their affiliated

DMMs and other market makers, investor costs might be different on these exchanges. The regressions show that DMMP trades have lower quoted spreads but higher effective spreads. Consistent with past research, we show that higher option delta leads to wider spreads. A more volatile or illiquid underlying also widens spreads.

Options features and market conditions may also impact market maker revenues even after accounting for the initial and dynamic hedge costs. The regressions for market maker revenues are reported in the final column. Market maker revenues are lower in auctions than in continuous trades. On a per-trade basis, the auction coefficients are between 2.6 and 3.05 cents lower for non-PFOF auctions on non-DMMP exchanges and between 1 and 0.24 cents lower for PFOF auctions on DMMP exchanges. PFOF revenues are between 0.78 and 0.69 cents higher than non-PFOF revenues in continuous trading on DMMP exchanges. PFOF auction revenues are lower by between 1.80 and 0.92 cents relative to PFOF continuous trading. Revenues on DMMP exchanges are higher.

Taken together, the results are consistent with the descriptive statistics that PFOF DMMs earn positive profits in continuous trades and may lose money in auctions. The fact that PFOF generate higher revenues in continuous trading may explain their ability to purchase more orders than other market makers.

3. Order Routing, Auctions, and Competition for Order Flow

Nonrandom order routing could stem from PFOF DMMs more often being at the best price or from possible conflicts of interest if those orders could receive better prices elsewhere.[30] FINRA Rule 5310 covers best execution and highlights executing brokers' duties to find price improvement opportunities.[31] Executing brokers, including wholesalers, must meet their best execution obligation on every order. Favorable prices for orders executing in continuous trading on exchanges can be measured relative to the best available quote across all markets.

To capture routing decisions to auctions and continuous trading, Figure 2 plots volume overall, for PFOF, and non-PFOF, as well as for auctions and continuous trading. The majority of orders are executed in continuous trading. PFOF trading volume is roughly 37% overall with 16% auction volume and 20% in continuous trading.

That PFOF wholesalers (WS) are more likely to route to auctions suggests that they purchase more retail orders from retail brokers that expect price improvements. Wholesalers purchase order flow and have execution priority at DMMP exchanges. To study wholesalers' order routing decisions, we regress

[30] For a discussion of the possible conflict, see page 33 of the SEC Best Execution Proposal.

[31] See FINRA Rule 5310.

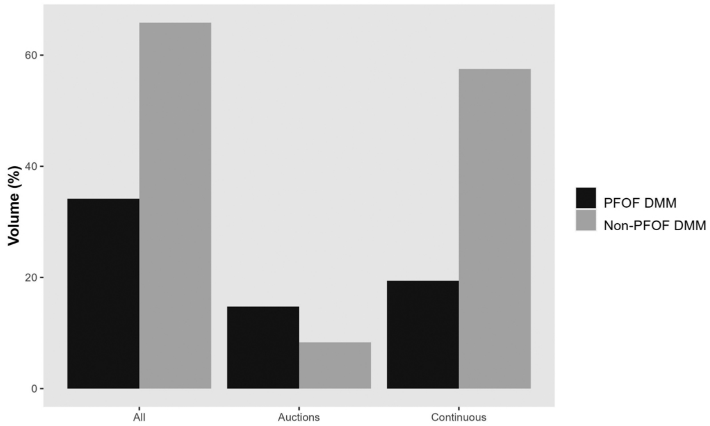

Figure 2
DMM volumes
This figure illustrates the traded volume for designated market makers, comparing those that pay significant payment for order flow with non-PFOF DMMs. The bars represent the volume across all trades, auctions, and continuous trading. Our sample period is the second half of 2020: August 2020 through December 2020.

the market share per underlying on a dummy variable that takes the value of 1 when the DMM is a top-four PFOF wholesalers, and zero otherwise. The largest PFOF DMMs have wholesaling arms that purchase the most contracts, and if they direct these contracts to exchanges where they are the DMM, our regression should capture this effect. We include a dummy variable for DMMP exchanges to account for general routing differences between DMMP and non-DMMP exchanges. In panel A, we report average volume for PFOF and non-PFOF for all, auction, and continuous trading, and for $\leq$ and $>$ 5 contracts. We also run regressions for all trades in panel B, for auction trades in panel C, and for continuous trades separately in panel D. For each, we include a specification for trades for $<=$ 5 and for $>$ 5 contracts.

The results are reported in Table 7. In panel A, we show that PFOF are more likely to run auctions unconditionally and for small and large trades. Bryzgalova, Pavlova, and Sikorskaya (2022) use auctions and small trades as a proxy for retail trading. They suggest that retail trading may be in excess of 60% of total option volume and that investors' options investment lose money. We show that purchased option volume covered by Rule 606 is between 48% and 59% of total option volume, as detailed in the Appendix in Table A3. PFOF WS that purchase orders must offer price improvement as well as PFOF to attract the orders from retail brokers. We find that PFOF DMMs with wholesaler arms that purchase orders have auction volumes of 14.75%. In the previous section, we also show that these orders receive the highest amount of price improvement, making them the most likely retail orders. In order to fund the PFOF to retail brokers, WS can also self-route orders to their affiliated

Table 7
PFOF volume

A: Volume distribution

				Contracts ≤ 5		Contracts > 5	
	All	Auction	Continuous	Auction	Continuous	Auction	Continuous
PFOF	34.16	14.75	19.41	6.99	10.47	7.76	8.94
Non-PFOF	65.84	8.32	57.51	3.58	28.41	4.74	29.10

B: All trades

	All	Contracts ≤ 5	Contracts > 5
PFOF	0.479***	0.401***	0.410***
	(0.034)	(0.035)	(0.043)
DMMP	0.088***	0.721***	–0.403***
	(0.029)	(0.029)	(0.038)
R^2	0.004	0.005	0.001
NObs	828,602	828,602	828,602

C: Auctions

	All	Contracts ≤ 5	Contracts > 5
PFOF	0.717***	0.416***	0.968***
	(0.067)	(0.064)	(0.088)
DMMP	6.111***	6.461***	5.824***
	(0.055)	(0.052)	(0.074)
R^2	0.029	0.033	0.019
NObs	566,888	566,888	566,888

D: Continuous trading

	All	Contracts ≤ 5	Contracts > 5
PFOF	0.459***	0.471***	0.325***
	(0.038)	(0.040)	(0.044)
DMMP	–1.511***	–0.827***	–2.096***
	(0.032)	(0.032)	(0.040)
R^2	0.005	0.003	0.005
NObs	828,602	828,602	828,602

This table presents distribution and regression results for PFOF versus non-PFOF option volume. Panel A presents trading volumes expressed as a percentage of the total trading volume. Panels A, B, and C present regression results for daily option trading volume for an underlying at a given exchange as a percent of total trading volume for the underlying. *PFOF* is an indicator variable that equals one if the trade is executed at an exchange where the designated market maker pays significant payment for order flow, and zero otherwise. *DMMP* is an indicator variable that equals one if the exchange has DMM order preferencing, and zero otherwise. The sample period is the second half of 2020: August 2020 through December 2020. All specifications include underlying fixed effects. Standard errors are double-clustered at the option and day level and are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

DMMs in continuous trading. These orders comprise 19.41% of the market and 10.47% for small orders in continuous trading.

We test the hypothesis that PFOF self-route in a regression setting. The PFOF coefficient is positive across all specifications. This is consistent with PFOF wholesalers routing the orders that they purchase to their affiliated DMMs. For a given underlying on an exchange, 0.48% more volume is routed to a PFOF-paying DMM than to a non-PFOF DMM. The average exchange should have a market share of 6.25%, and an increase of 0.48% represents more than 7.5% more trading volume. In auctions, wholesalers also appear to route more orders to their affiliated DMMs. If DMMs take advantage of their small order priority in continuous trading, we expect the coefficient to be larger. Panel D presents evidence consistent with this. The coefficient for small orders is positive and larger for small orders than it is for large orders. The coefficient on PFOF for large trades in auctions is consistent with PFOF WS routing small orders to continuous trading and large orders to auctions. PFOF have priority in continuous trading for small trades and can use the fee and priority advantages of auction initiators for large trades.

Overall, these results suggest that PFOF route smaller orders to continuous trading where their affiliated DMMs have priority, and larger orders to auctions. Order routing can also be related to a number of factors, including marketing and break-up fees, fee caps, and other market features unrelated to DMM assignments. These nuances may explain why the PFOF DMM order routing effect is smaller than the total quantity of orders purchases by PFOF.

3.1. Auctions

Auctions are an important feature of options markets and comprise roughly 23% of all volume. When and why auctions are run can be explained by a number of factors. Because a DMM or other market maker must choose to run an auction and is typically required to execute the opposite side of the auction, they will take a number of factors into consideration. We estimate a linear probability model that takes the value 1 for auctions and 0 for continuous trades. The results are reported in Table 8.

In the regression, we control for date and underlying fixed effects, option characteristics, trade characteristics, and market conditions. An important factor is whether or not the trade may be arbitraging recent price changes in the underlying. We calculate an arbitrage variable as trades in the option in the same direction as the 5-second return in the underlying. For instance, if the price of the underlying moves up in the previous 5 seconds and we observe a subsequent buy for a call, we would classify that trade as an arbitrage trade. We show that arbitrage trades are less likely to go to auctions and more likely to be routed to continuous trading. Auctions are also more likely when the option quoted spread is wide. If quotes move based on the initiation of an auction in a correlated way, for example, when an auction where the customer is buying causes quotes to increase, then the price improvement in auctions could be overstated. If auction initiation causes a systematic widening or narrowing of quotes, then our comparisons will be incorrect. Wider quoted spreads make it easier for DMMs to offer price improvement in auctions, and investors likely care about executions happening at extremely wide effective spreads. Both of these reasons can drive DMMs to run more auctions when spreads are wide. High delta and high underlying spread make auctions less likely. Overall, the auction result suggests that DMMs run auctions when they can provide more price improvement for customers and when market making costs are likely to be lower.

Table 8
Auction LPM

	(1)	(2)	(3)
PFOF	0.036***	0.036***	0.035***
	(0.004)	(0.004)	(0.004)
$Arbitrage_{t-1}$	–0.290***		–0.295***
	(0.012)		(0.012)
Option Quoted Spread		0.081***	0.149***
		(0.000)	(0.000)
DMMP	0.331***	0.331***	0.329***
	(0.003)	(0.003)	(0.003)
|Delta|			–0.044***
			(0.002)
Gamma			0.009*
			(0.005)
Vega			–0.033***
			(0.001)
Underlying Quoted Spread			–0.018***
			(0.000)
1/Option Midpoint			–0.004***
			(0.000)
1/Underlying Midpoint			0.880***
			(0.117)
Underlying MCAP			0.004
			(0.008)
Trade size			0.010***
			(0.000)
Call			0.039***
			(0.001)
Days-to-Expiry			–0.023***
			(0.001)
Tick Size			–0.007***
			(0.001)
Buy			–0.007***
			(0.001)
R^2	0.186	0.186	0.196
NObs	78,893,354	78,893,354	78,893,354

This table presents results from a linear probability model for auctions. The dependent variable is a binary variable that equals one if the trade is executed as an auction, and zero otherwise. *Arbitrage* is the product of call/put direction indicator, option buy/sell direction indicator, and underlying stock return prior to option trade. *PFOF* is an indicator variable that equals one if the trade is executed at an exchange where the designated market maker pays significant payment for order flow, and zero otherwise. *Quoted spread* for options and underlying stocks are scaled to dollars for this table. All dependent variables are defined in Table A2. Our sample period is the second half of 2020: August 2020 through December 2020. All specifications include underlying and day fixed effects. Standard errors are double-clustered at the underlying and day level and are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

3.2. Wholesaler competition for orders

When wholesalers purchase orders from brokers, they pay the same amount per contract and order type, depending on market conditions, and compete with other PFOF-paying wholesalers on execution quality (frequency of price improvement, EQ ratio, and price improvement). Price improvement can be attained in continuous trading, but price-improving orders are hidden and may be difficult to predict. Auctions provide wholesalers with a mechanism to provide price improvement directly to the orders that they purchase. Brokers advertise the amount and frequency of the price improvement that their orders receive. For equity trades, for example, Schwab reports the number of shares executed at best prices or better, the percentage of shares that receive price improvement, average savings per order, and average execution speed. These data are required disclosure for equity orders by Rule 605 but are not required for option trades. Nevertheless brokers will compare wholesalers' execution quality using similar measures. An additional measure often used in options markets is the EQ ratio.

To characterize wholesaler competition, we compute the average auction frequency excluding the executing DMM, EQ ratio, and total price improvement for all PFOF-paying DMMs disclosed in Rule 606 disclosures. We compare the auction frequency, EQ ratio, and price improvement for a specific PFOF-paying DMM to the average minus that DMM's auction frequency, EQ, or price improvement. We set an indicator value equal to one if the DMM is above the average EQ or below the average price improvement or auction frequency. The indicator variable captures whether or not a specific DMM is above or below their competitors.

To improve their execution statistics, wholesalers can offer more frequent price improvement, more price improvement, or both. If a DMM has below average price improvement frequency or size in a month, they may receive fewer orders in the following months. To analyze competition in the PFOF market, we regress a variable that takes the value 1 if one of the four top PFOF-paying DMMs runs an auction, and 0 if a smaller PFOF-paying DMM runs an auction.[32] We limit the analysis to the Rule 606 DMMs, as these are the wholesaler (DMMs) that are in competition for broker order flow. Table 9 reports results of the regression focusing on prior execution quality.

The results show that large PFOF-paying DMMs run relatively more auctions when their own EQ is above average, and their price improvement and auction frequency is below average. To control for the fact that PFOF-paying DMMs are likely to run more auctions overall, we include a variable that controls for the percent of total contracts purchased by a wholesaler. As expected, this variable is positive in all three regressions. Next we use our regression model to analyze the effect of execution quality relative to competitors. Table 10 reports results of the regression focusing on execution quality relative to competitors.

The overall results illustrate that large PFOF-paying DMMs tend to run relatively more auctions when their own EQ is above that of their competitors, while their price improvement and auction frequency are lower compared to their competitors. Auction frequency is relatively well explained by our regressions, with r-squared ranging from 70% to 84%. These results suggest that the large PFOF-paying DMMs monitor the executions being offered by other DMMs. Large DMMs should be more competitive than small DMMs if they want to continue to receive a large number of orders. When their execution

[32] We cannot observe the identity of the MM running an auction. Here, we assume that the DMM appointed in continuous trading for that underlying is also likely to run auctions.

Table 9
PFOF LPM: DMMs' execution quality comparison with previous month

	(1)	(2)	(3)
EQ Above Average$_{t-1}$	0.239***		
	(0.014)		
Price Improvement Below Average$_{t-1}$		0.069***	
		(0.012)	
Auction Frequency Below Average$_{t-1}$			0.031***
			(0.011)
Contract Purchases (%)	0.017***	0.017***	0.017***
	(0.000)	(0.000)	(0.000)
|Delta|	0.024***	0.021***	0.022***
	(0.002)	(0.002)	(0.002)
Option Quoted Spread	–0.010***	–0.010***	–0.010***
	(0.001)	(0.001)	(0.001)
Gamma	–0.018***	–0.025***	–0.023***
	(0.004)	(0.003)	(0.003)
Vega	–0.001	–0.001	–0.001
	(0.001)	(0.001)	(0.001)
Underlying Quoted Spread	0.005***	0.006*	0.007
	(0.004)	(0.002)	(0.002)
1/Option Midpoint	–0.002***	–0.003***	–0.003***
	(0.000)	(0.000)	(0.000)
1/Underlying Midpoint	–0.544***	0.073	–0.196*
	(0.194)	(0.142)	(0.106)
Underlying MCAP	–0.077***	–0.003	–0.032***
	(0.011)	(0.009)	(0.007)
Trade size	–0.008***	–0.009***	–0.009***
	(0.000)	(0.000)	(0.000)
Call	–0.003***	–0.003***	–0.003***
	(0.001)	(0.000)	(0.000)
Days-to-Expiry	–0.001***	–0.002***	–0.002***
	(0.000)	(0.000)	(0.000)
Tick Size	–0.012***	–0.017***	–0.016***
	(0.001)	(0.001)	(0.001)
Buy	0.001**	0.001**	0.001**
	(0.000)	(0.000)	(0.000)
R^2	0.708	0.681	0.679
NObs	12,109,289	12,109,289	12,109,289

This table presents results from a linear probability model for auctions at exchanges where the designated market maker pays payment for order flow Rule 606 DMMs. The dependent variable is a binary response variable that equals one if the trade is executed at an exchange where the DMM pays significant PFOF, and zero otherwise. *EQ Above Average*, *Price Improvement Below Average*, *Auction Frequency Below Average* are indicator variables comparing execution quality to previous month's performance. *Quoted spread* for options and underlying stocks are scaled to dollars. All dependent variables are defined in Table A2. Our sample period is the second half of 2020: August 2020 through December 2020. All specifications include underlying and day fixed effects. Standard errors are double-clustered at the underlying and day level and are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

statistics fall behind those of other DMMs, they increase the frequency of auctions that can lead to price improvement.

While auctions can generate price improvement, a higher frequency of auctions does not necessarily lead to higher price improvement. To capture the amount of price improvement, we regress the EQ ratio and price improvement on a PFOF indicator variable that captures whether that DMM is above (EQ) or below (price improvement) the PFOF-paying DMMs' average, and the interaction of both variables. The results are reported in Table 11.

Table 10
PFOF LPM: DMMs' execution quality comparison with competitors

	(1)	(2)	(3)
EQ Above$_{i,t-1}$	0.508***		
	(0.007)		
Price Improvement Below$_{i,t-1}$		0.277***	
		(0.009)	
Auction Frequency Below$_{i,t-1}$			0.534***
			(0.006)
Contract Purchases (%)	0.018***	0.022***	0.022***
	(0.000)	(0.000)	(0.000)
|Delta|	0.005*	–0.000	–0.001
	(0.003)	(0.004)	(0.003)
Option Quoted Spread	–0.009***	–0.004***	–0.004***
	(0.001)	(0.001)	(0.001)
Gamma	–0.027***	–0.023***	–0.031***
	(0.003)	(0.004)	(0.003)
Vega	0.001	–0.001	0.000
	(0.000)	(0.001)	(0.000)
Underlying Quoted Spread	–0.014***	–0.002	–0.014***
	(0.004)	(0.004)	(0.003)
1/Option Midpoint	–0.003***	–0.003***	–0.001***
	(0.000)	(0.000)	(0.000)
1/Underlying Midpoint	–0.003	–0.462***	0.530***
	(0.107)	(0.161)	(0.070)
Underlying MCAP	0.011	–0.004	0.044***
	(0.008)	(0.012)	(0.005)
Trade size	–0.009***	–0.009***	–0.004***
	(0.000)	(0.000)	(0.000)
Call	–0.000	–0.002***	–0.000
	(0.001)	(0.001)	(0.000)
Days-to-Expiry	–0.004***	–0.004***	–0.002***
	(0.000)	(0.000)	(0.000)
Tick Size	–0.021***	–0.022***	–0.012***
	(0.001)	(0.001)	(0.001)
Buy	–0.000	–0.000	–0.000
	(0.000)	(0.000)	(0.000)
R^2	0.698	0.721	0.844
NObs	12,109,289	12,109,289	12,109,289

This table presents results from a linear probability model for auctions at exchanges where the designated market maker pays payment for order flow Rule 606 DMMs. The dependent variable is a binary response variable that equals one if the trade is executed at an exchange where the DMM pays significant PFOF, and zero otherwise. Subscript i denotes indicator variables for DMM i, that are constructed to compare DMM i's execution quality with those of its competitors. *Quoted spread* for options and underlying stocks are scaled to dollars. All dependent variables are defined in Table A2. Our sample period is the second half of 2020: August 2020 through December 2020. All specifications include underlying and day fixed effects. Standard errors are double-clustered at the underlying and day level and are reported in parentheses. *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

Within the set of auctions run by PFOF-paying DMMs, the largest PFOF DMMs have slightly lower EQ than the smaller DMMs. When PFOF-paying DMMs are above the average EQ, they do not appear to offer better executions as measured by EQ. In terms of price improvement, the large PFOF-paying DMMs offer less price improvement, and, if their average price improvement is below average, they increase the amount of price improvement that they offer relative to other DMMs. The results are likely driven by the fact that DMMs run more auctions when the EQ and price improvement are above (or below) average. A higher auction frequency is likely to lead to lower average price

Table 11
PFOF auctions and competition

	EQ	*Price Improvement*
PFOF	–0.005*	–1.614***
	(0.003)	(0.239)
EQ Above$_{i,t-1}$	0.181***	
	(0.007)	
PFOF × *EQ Above*$_{i,t-1}$	–0.007	
	(0.006)	
Price Improvement Below$_{i,t-1}$		–1.274***
		(0.217)
PFOF × *Price Improvement Below*$_{i,t-1}$		1.102***
		(0.273)
Contract Purchases (%)	0.001***	0.011**
	(0.000)	(0.005)
|Delta|	–0.159***	27.353***
	(0.006)	(1.063)
Gamma	0.170***	–13.283***
	(0.008)	(0.909)
Vega	0.002*	19.790***
	(0.001)	(0.814)
Underlying Quoted Spread	–0.043***	31.583***
	(0.004)	(1.880)
1/Option Midpoint	0.026***	1.460***
	(0.001)	(0.066)
1/Underlying Midpoint	–0.800***	–74.724***
	(0.141)	(19.355)
Underlying MCAP	–0.043***	4.033**
	(0.008)	(1.756)
Trade size	0.017***	–0.207***
	(0.000)	(0.015)
Call	0.029***	–1.574***
	(0.001)	(0.105)
Days-to-Expiry	–0.013***	1.449***
	(0.001)	(0.118)
Tick Size	0.073***	1.047***
	(0.003)	(0.267)
Buy	–0.009***	0.017
	(0.001)	(0.017)
R^2	0.137	0.450
NObs	12,109,289	12,109,289

This table presents regression results for PFOF *effective spread* to *quoted spread* (*EQ*), *price improvement* and competition for auctions at exchanges where the designated market maker (DMM) pays payment for order flow Rule 606 DMMs. *PFOF* is an indicator variable that equals one if the trade is executed at an exchange where the designated market maker pays significant for order flow and zero otherwise. Subscript *i* denotes indicator variables for DMM *i*, which are constructed to compare DMM *i*'s execution quality with those of its competitors. *Quoted spread* for options and underlying stocks are scaled to dollars. All dependent variables are defined in Table A2. Our sample period is the second half of 2020: August 2020 through December 2020. Standard errors are double-clustered at the underlying and day level and are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

improvement. It may also be the case that the DMMs cannot offer more price improvement and that they initiate auctions in the hopes that other participants will price improve the orders.

Trades that are routed to auctions often receive little to no price improvement. The minimum price improvement is most often 0 cents but can also be 1 cent. In Figure 3, we plot the frequency of price improvement for 0 cents, 1 cent, between 2 and 9 cents, and greater than 10 cents. 0-cent price improvement is most frequent at roughly 25% of all auction trades, followed by 1-cent price

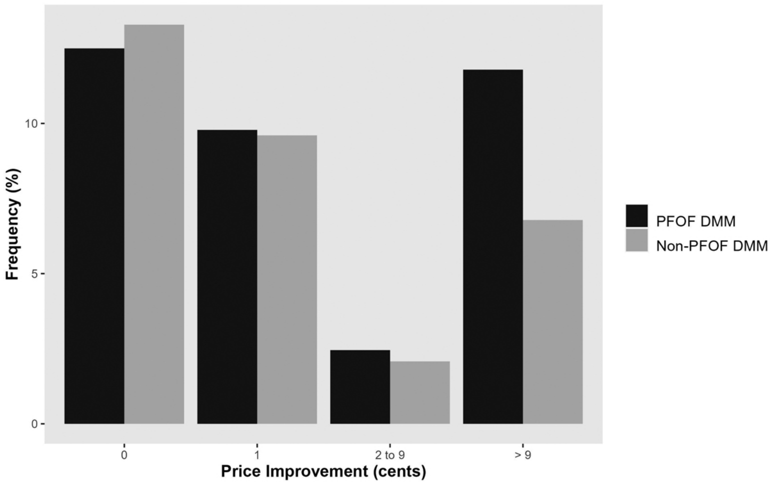

Figure 3
Auction frequency versus price improvement
This figure plots *auction frequency* against *price improvement measured* in cents. It compares the frequency of auctions, for designated market makers that pay significant payment for order flow versus non-PFOF DMMs. Minimum price improvement is either 0 or 1 cent at all exchanges. Frequency for the 2- to 9-cent price improvement range is averaged across this 8-cent increment. The sample period covers the second half of 2020, from August to December.

improvement with roughly 20% of all trades. We combine all trades with price improvement greater than 10 cents, and these comprise roughly 18% of all auctions.

We plot these measures for PFOF DMMs and non-PFOF and show that PFOF DMMs are more likely to provide greater-than-minimum price improvement. This shows not only that PFOF DMMs run auctions more frequently, but also that they price-improve orders more frequently than non-PFOF DMMs.[33]

The OPRA data feed reports trades with multiple counterparties as multiple prints. We combine trades in the same option, on the same exchange, at the same time into a single trade and count the number of prints per trade. We find that trades with minimal price improvements have the highest frequency of trades with multiple counterparties. This is driven by the high number of multiple print trades for non-PFOF. We do not observe the participants in auctions, so can only infer behaviors. A higher frequency of multiple prints at minimal price improvement suggests that a common bidding strategy is for initiating MMs to offer minimum price improvement and for noninitiating auction responders to also offer minimal price improvement. One way to interpret the decreasing frequency of multiple prints as price improvement

[33] In Appendix Table A5, we report descriptive statistics for multi-print and minimum price improvement auctions.

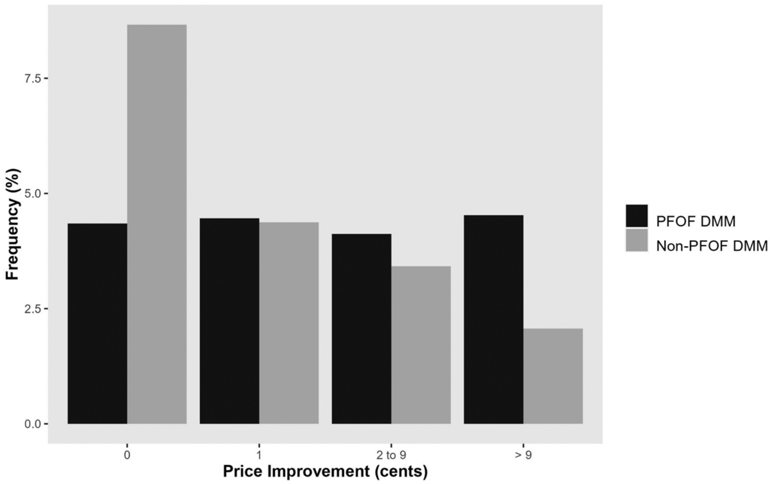

Figure 4
Auction competition with multiple bidders
This figure plots frequencies for auctions with multiple bidders against *price improvement* measured in cents, comparing those executed by designated market makers that pay significant payment for order flow versus non-PFOF DMMs. Frequency is measured relative to total number of auctions within the given price improvement. Minimum *price improvement* is either 0 or 1 cent at all exchanges. Frequency for the 2- to 9-cent *price improvement* range is averaged across this 8-cent increment. The sample period covers the second half of 2020, from August to December.

increases is that initiating dealers submit auto-matching orders and fewer better-priced orders are submitted for higher amounts of price improvement.

In Figure 4, we find that, for auctions with price improvement greater than 9 cents, PFOF trades are more than twice as likely to have multiple bidders. This suggests that PFOF bidders are more likely to match at higher levels of price improvement than non-PFOF bidders.

The results suggest that competition occurs via auction frequency and via aggressive bidding in auctions. This may be the case because wholesalers compete by offering PFOF and better client executions when bidding on orders from brokers. In order to receive more orders, wholesalers must offer frequent and large price improvement. Price improvement can only be guaranteed by running auctions. However, because of asymmetric fees and other noncompetitive features of auctions, other bidders are discouraged from responding, leading to less than 10% of auctions attracting multiple bidders at the winning price. Thus, the frequent and large price improvement in auctions is likely a reflection of the price improvement a wholesaler offers in order to continue to receive orders from brokers.

4. Conclusion

Regulators and academics have shown substantial recent interest in payment for order flow and retail trading. With limited justification, the SEC has asserted that requiring all marketable retail equity orders to be exposed to auctions would enhance retail execution quality over the status quo. PFOF and retail trading are substantially larger in options markets than in equity. In addition, options markets already have price improvement auctions similar to those proposed by the SEC for stocks. Furthermore, options exchanges have designated market makers who purchase retail order flow.[34] This structure allows us to better understand how wholesalers compete for retail option orders and provides insights into how the proposed retail auctions for equities may perform.

Our results are consistent with PFOF and auctions leading to competition and improved execution for retail option orders. Auctions occur in options with wide spreads and have large price improvement and low or negative market maker revenues. PFOF DMM auctions occur in options where spreads are even wider, but provide large price improvement, leading to lower and negative market maker revenues. PFOF wholesalers run more auctions with higher price improvement when their recent price improvement has been lower. These results are consistent with PFOF wholesalers using auctions to manage their execution statistics to compete for retail orders.

While auctions appear to yield competitive outcomes on average,[35] there is substantial variation across auctions. Auctions result in minimum price improvement more than 45% of the time and less than 10% of auctions have more than one bidder at the winning price. These multiple winning bidder auctions most frequently occur in minimum price improvement auctions where the wholesaler initiating the auction is required to participate. This is consistent with the competitive options auction results stemming from wholesalers competing for retail orders across all orders and not on an order-by-order basis. The SEC's proposed Order Competition Rule does not include participation incentives, thereby reducing or removing the incentives for the wholesaler to bid in stock auctions. Thus, extrapolating from options auctions suggests that 90% of equity auctions may fail to attract any bidders and receive price improvement. Therefore, the SEC proposal's costs may substantially outweigh its benefits.

Our findings on nonauction continuous trades suggest limited competition in the options market, as both quoted and effective spreads are wide, and market maker revenues are large. PFOF-designated market makers tend to trade in options with wider spreads and smaller price improvements, leading to larger effective spreads and higher revenues. This is likely driven by preferential DMM allocation rules, which reduce competition in nonauctions and allow wholesalers to generate revenue to cover PFOF costs. However, further research using trader-identified data or exogenous variations in DMMs

[34] A 2021 SEC staff report on equity and options market structure conditions estimates that wholesalers in the listed options market generally internalize approximately 31% of the executed orders routed to option exchanges, with about 73% of orders routed to price improvement auctions, and 17% to continuous trading being internalized.

[35] One benchmark for auction competition is market maker revenues that are negative in auctions.

and PFOF is needed to establish causal links between wide option spreads, PFOF practices, and DMM priority. It is also important to understand whether the significant consolidation in the options market-making sector (Banerji 2017) is due to DMM preferencing making it difficult for smaller market makers to compete or high fixed costs associated with the large number of options and exchanges relative to trading volume. Given these factors, further research on the causes of illiquidity in the options market is warranted.

Code Availability: The replication code and data are available in the Harvard Dataverse at https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/LMB13N.

Appendix

A1. Appendix Tables

Table A1
Matched descriptive statistics

	Continuous Trading		Auction Trades	
	PFOF	Matched Non-PFOF	PFOF	Matched Non-PFOF
Option Midpoint	14.40	14.24	7.11	6.57
|Delta|	0.35	0.34	0.36	0.36
Days to Exp.	21.27	20.40	19.58	19.39
Trade size (contracts)	3.68	3.70	4.83	4.30
Number of Trades	6,766,806	6,766,806	6,173,987	6,173,987

This table presents sample means for the treated (PFOF) and matched sample (non-PFOF). We retain continuous trades that are within 5 seconds of auction trades for the identical underlying symbol and option type (call or put). The treated sample is the set of option trades that executed on an exchange where the DMM pays a significant amount of order flow. We match the treated sample to non-PFOF DMM trades based on seven trade characteristics: i) underlying symbol, ii) trade type (continuous trading or auction), iii) option type (put or call), iv) date on which the trade executed, v) prevailing option midpoint at the time of the trade, vi) trade size measured in contracts, and vii) delta of the option. For the first four variables, we require an identical match. We then use propensity score matching to match on the option midpoint, trade size, and option delta.

Table A2
Definition of variables

Variable	Definition	Source
PFOF	Indicator variable that equals 1 if the trade is executed for an underlying symbol at an exchange where the DMM pays significant payment for order flow, and zero otherwise.	OPRA & Rule 606
Auction	Indicator variable that equals 1 if trade is executed as an auction, and zero otherwise.	OPRA
$Arbitrage_{t-1}$	Product of call/put direction indicator, option buy/sell direction indicator and underlying return from 5 seconds prior to option trade. Call/put direction indicator equals 1 (-1) if the option traded is a call (put). Buy/sell direction indicator equals 1 (-1) if the option trade is initiated by a buyer (seller).	OPRA & TAQ
$EQ\ Above\ Average_{t-1}$	Indicator variable that equals 1 if the average auction EQ for the prior day is larger than the average daily EQ for the prior month, and zero otherwise.	OPRA & Rule 606
$Price\ Improvement\ Below\ Average_{t-1}$	Indicator variable that equals 1 if the total auction price improvement for the prior day is smaller than the average daily price improvement for the prior month, and zero otherwise.	OPRA & Rule 606
$Auction\ Frequency\ Below\ Average_{t-1}$	Indicator variable that equals 1 if the total auction frequency for the prior day is smaller than the average daily auction frequency for the prior month, and zero otherwise.	OPRA & Rule 606
$EQ_{-i,t-1}$	Leave-one-out average auction EQ for Rule 606 DMM i defined as follows: rolling monthly average of auction EQ for all Rule 606 DMMs except DMM i. The rolling average is computed as of 1 day prior to the option trade.	OPRA & Rule 606
$EQ_{i,t-1}$	Average auction EQ for Rule 606 DMM i defined as follows: rolling monthly average of auction EQ for DMM i. The rolling average is computed as of 1 day prior to the option trade.	OPRA & Rule 606
$EQ\ Above_{i,t-1}$	Indicator variable that equals 1 if $EQ_{i,t-1}$ is larger than $EQ_{-i,t-1}$, and zero otherwise.	OPRA & Rule 606
$Price\ Improvement_{-i,t-1}$	Leave-one-out total auction price improvement for DMM i defined as follows: rolling monthly sum of total price improvement for all Rule 606 DMMs except DMM i. The rolling sum is computed as of 1 day prior to the option trade and normalized by number of DMMs excluding DMM i.	OPRA & Rule 606
$Price\ Improvement_{i,t-1}$	Total auction price improvement for Rule 606 DMM i defined as follows: rolling monthly sum of total price improvement for DMM i. The rolling sum is computed as of 1 day prior to the option trade.	OPRA & Rule 606
$Price\ Improvement\ Below_{i,t-1}$	Indicator variable that equals 1 if $Price\ Improvement_{i,t-1}$ is smaller than $Price\ Improvement_{-i,t-1}$, and zero otherwise.	OPRA & Rule 606
$Auction\ Frequency_{-i,t-1}$	Leave-one-out total auction frequency for DMM i defined as follows: rolling monthly sum of auction frequency for all Rule 606 DMMs except DMM i. The rolling sum is computed as of 1 day prior to the option trade and normalized by number of DMMs excluding DMM i.	OPRA & Rule 606
$Auction\ Frequency_{i,t-1}$	Total auction frequency for Rule 606 DMM i defined as follows: rolling monthly sum of auction frequency for DMM i. The rolling sum is computed as of 1 day prior to the option trade.	OPRA & Rule 606
$Auction\ Frequency\ Below_{i,t-1}$	Indicator variable that equals 1 if $Auction\ Frequency_{i,t-1}$ is smaller than $Auction\ Frequency_{-i,t-1}$, and zero otherwise.	OPRA & Rule 606
$\|Delta\|$	Absolute value of the option's delta.	OPRA
Trade size	Logarithmic of option trade size (in contracts).	OPRA
Call	Indicator variable that equals 1 if the option traded is a call option.	OPRA
Days-to-expiration	Logarithmic of number of days to option expiration.	OPRA

(Continued)

Table A2
(Continued)

Variable	Definition	Source
Initial Hedge Cost	Product of underlying quoted spread prevailing at the time of option trade and the absolute value of option delta.	OPRA & TAQ
Dynamic Hedge Cost	Following Leland (1985), proportional to the product of option vega, underlying quoted spread and re-balancing frequency.	OPRA & TAQ
Gamma	Gamma of the option at the time of trade.	OPRA
Vega	Vega of the option at the time of trade.	OPRA
Underlying Quoted Spread	Underlying quoted spread prevailing 1 millisecond prior to option trade.	TAQ
Underlying Volatility	Underlying return size computed from midpoints prevailing 5 seconds prior to option trade.	TAQ
1/Underlying Midpoint	Reciprocal of underlying midpoint prevailing 1 millisecond prior to option trade.	TAQ
1/Option Midpoint	Reciprocal of option midpoint prevailing at the time of option trade.	OPRA
Underlying MCAP	Logarithmic of underlying market capitalization (MCAP).	TAQ
Tick Ind.	Indicator variable that equals 1 if the option price is less than \$3. Option tick size changes when an option is trading above \$3.	OPRA

This table presents descriptions of variables used in our regression and linear probability models.

Table A3
Rule 606 implied volume

DMM	Contracts Purchased Million	Implied Volume (%)	Implied Volume (%) Merged TAQ
All	309.97	48.20	58.58
Citadel	138.68	21.56	26.21
Susquehanna	84.89	13.21	16.05
Wolverine	29.51	4.59	5.58
Dash	30.83	4.80	5.83
Morgan Stanley	13.06	2.02	2.46
WEX	3.78	0.59	0.72
Group One	7.95	1.24	1.50
Two Sigma	0.93	0.14	0.17
Matrix	0.46	0.07	0.08
Citigroup	0.32	0.05	0.06

This table displays the distribution of contracts purchased by wholesalers from Rule 606 filings for the largest brokers. Column 1 shows the total number of contracts purchased. Column 2 presents contracts purchased as a percentage of the total trading volume for all options listed on public exchanges in the OptionMetrics database. Column 3 presents contracts purchased as a percentage of the total trading volume for options with underlying symbols common to both the OptionMetrics and TAQ databases. All reported statistics are monthly averages. Our sample period covers the second half of 2020, from August through December.

Table A4
Execution quality, revenues, auctions, and PFOF DMMs relative to option midpoint

A: Full sample

	Quoted Spreads	*Effective Spreads*	*Price Improvement*	*MM Rev.*
Auction	0.81***	–0.47***	1.50***	–0.52***
	(0.01)	(0.01)	(0.02)	(0.01)
PFOF	0.02***	0.14***	–0.15***	0.17***
	(0.01)	(0.01)	(0.01)	(0.01)
Auction × PFOF	–0.01	–0.18***	0.20***	–0.21***
	(0.01)	(0.01)	(0.01)	(0.01)
DMMP	–0.16***	0.19***	–0.42***	0.22***
	(0.00)	(0.00)	(0.01)	(0.00)
|Delta|	–4.39***	–3.39***	–1.20***	–3.01***
	(0.07)	(0.05)	(0.02)	(0.06)
Gamma	2.50***	1.85***	0.70***	–0.33***
	(0.10)	(0.07)	(0.04)	(0.08)
Vega	–0.47***	–0.29***	–0.26***	–0.08***
	(0.02)	(0.02)	(0.01)	(0.02)
Underlying Volatility$_{t-1}$	3.66***	2.56***	1.31***	
	(0.21)	(0.14)	(0.08)	
Underlying Quoted Spread	0.01***	0.01***	0.01***	
	(0.00)	(0.00)	(0.00)	
1/Underlying Midpoint	22.30***	17.57***	4.80***	8.10***
	(1.57)	(1.04)	(1.00)	(1.91)
Underlying MCAP	1.06***	0.76***	0.39***	0.88***
	(0.10)	(0.07)	(0.04)	(0.13)
Trade size	0.04***	0.05***	–0.01***	0.04***
	(0.00)	(0.00)	(0.00)	(0.00)
Call	–0.04***	–0.03***	–0.02***	–0.31***
	(0.01)	(0.01)	(0.00)	(0.01)
Days-to-Expiry	–0.18***	–0.17***	0.02***	–0.12***
	(0.01)	(0.01)	(0.00)	(0.01)
Tick Size	0.54***	0.36***	0.26***	0.28***
	(0.04)	(0.03)	(0.01)	(0.03)
Buy	–0.02***	–0.02***	–0.01***	–0.04***
	(0.00)	(0.00)	(0.00)	(0.00)
R^2	0.34	0.31	0.10	0.14
NObs	78,893,354	78,893,354	78,893,354	78,893,354

(Continued)

Table A4
(Continued)

B: Matched sample

	Quoted Spreads	*Effective Spreads*	*Price Improvement*	*MM Rev.*
Auction	0.44***	–0.35***	0.88***	–0.38***
	(0.01)	(0.01)	(0.02)	(0.01)
PFOF	–0.11***	0.17***	–0.29***	0.18***
	(0.01)	(0.01)	(0.01)	(0.01)
Auction × *PFOF*	0.09***	–0.20***	0.31***	–0.22***
	(0.01)	(0.01)	(0.01)	(0.01)
DMMP	0.00	0.01	–0.00	0.00
	(0.00)	(0.00)	(0.01)	(0.01)
|*Delta*|	–3.61***	–2.64***	–1.20***	–2.01***
	(0.07)	(0.05)	(0.03)	(0.05)
Gamma	2.46***	1.89***	0.57***	–0.09
	(0.14)	(0.10)	(0.06)	(0.12)
Vega	–0.44***	–0.31***	–0.19***	–0.11***
	(0.02)	(0.01)	(0.01)	(0.02)
Underlying Volatility$_{t-1}$	3.04***	1.98***	1.23***	
	(0.19)	(0.12)	(0.09)	
Underlying Quoted Spread	0.01***	0.01***	0.01***	
	(0.00)	(0.00)	(0.00)	
1/Underlying Midpoint	20.25***	16.08***	3.29	7.49***
	(2.36)	(1.33)	(2.34)	(2.19)
Underlying MCAP	0.88***	0.58***	0.36***	0.74***
	(0.11)	(0.07)	(0.06)	(0.14)
Trade size	0.02***	0.04***	–0.03***	0.04***
	(0.00)	(0.00)	(0.00)	(0.00)
Call	–0.24***	–0.11***	–0.18***	–0.44***
	(0.02)	(0.01)	(0.01)	(0.02)
Days-to-Expiry	–0.07***	–0.09***	0.05***	0.01
	(0.01)	(0.01)	(0.00)	(0.01)
Tick Size	0.63***	0.43***	0.30***	0.32***
	(0.05)	(0.04)	(0.02)	(0.04)
Buy	–0.04***	–0.05***	–0.01***	–0.07***
	(0.00)	(0.00)	(0.00)	(0.00)
R^2	0.33	0.24	0.18	0.09
NObs	25,881,586	25,881,586	25,881,586	25,881,586

This table presents regression results for execution quality, expressed as a percentage relative to the option midpoint. *PFOF* is an indicator variable that equals one if the trade is executed at an exchange where the designated market maker (DMM) pays significant payment for order flow, and zero otherwise. *Auction* is an indicator variable that equals one if the trade is executed at an auction, and zero otherwise. All dependent variables are defined in Table A2. Our sample period is the second half of 2020: August 2020 through December 2020. All specifications include underlying and day fixed effects. Spreads are winsorized at the 1% level on each tail. Standard errors are double-clustered at the underlying and day level and are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table A5
Auction execution costs for minimum price improvement and multiple prints

A: Zero-cent price improvement

		All	PFOF	NPFOF	PFOF − NPFOF
Quoted Spread	Cents	2.34	2.56	2.13	0.43***
Effective Spread	Cents	2.34	2.56	2.13	0.43***
Trade Size	Contracts	7.88	8.81	6.99	1.81***
Trade Price	$	2.02	2.30	1.75	0.55***
Stock Midpoint	$	179.36	211.87	148.46	63.41***
Market Maker Revenues	Cents	1.05	1.03	1.07	–0.04
Hedge Cost	Cents	1.28	1.52	1.06	0.47***

B: One-cent price improvement

		All	PFOF	NPFOF	PFOF − NPFOF
Quoted Spread	Cents	2.50	2.61	2.38	0.22***
Effective Spread	Cents	1.50	1.61	1.38	0.22***
Trade Size	Contracts	5.11	5.23	4.98	0.24***
Trade Price	$	1.97	2.15	1.78	0.37***
Stock Midpoint	$	177.33	204.80	149.09	55.70***
EQ		0.39	0.40	0.38	0.02***
Market Maker Revenues	Cents	0.34	0.33	0.36	–0.03
Hedge Cost	Cents	1.15	1.27	1.03	0.25***

C: Multiple prints

		All	PFOF	NPFOF	PFOF − NPFOF
Quoted Spread	Cents	9.41	12.77	6.34	6.43***
Effective Spread	Cents	4.16	5.51	2.92	2.59***
Price Improvement	Cents	5.25	7.26	3.42	3.84***
Trade Size	Contracts	6.16	6.07	6.25	–0.19**
Trade Price	$	6.67	9.65	3.92	5.73***
Stock Midpoint	$	343.01	507.59	192.21	315.38***
EQ		0.48	0.46	0.51	–0.05***
Market Maker Revenues	Cents	0.10	−0.63	0.77	–1.40***
Hedge Cost	Cents	3.99	6.06	2.11	3.96***

This table presents average execution costs for trades that execute in auctions with 0-cent price improvement (panel A), 1-cent price improvement (panel B), and with multiple prints (panel C). *PFOF* denotes that the trade is executed at an exchange where the designated market maker pays significant payment for order flow, and NPFOF if otherwise. *Quoted spread* is half the difference of option ask and bid prices prevailing at the time of trade. *Effective spread* is the difference between option price and midpoint, times trade direction. *Price improvement* is the difference between option quoted spread and effective spread. *EQ* is the ratio of effective and quote spread. *Market maker revenues* is the difference between effective spread and hedge cost. *Hedge cost* is the sum of initial and dynamic hedge cost components. Our sample period is the second half of 2020: August 2020 through December 2020. Spreads are winsorized at the 1% level on each tail. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table A6
Execution costs for penny pilot program

A: Auctions

		All	PFOF	NPFOF	PFOF − NPFOF
Quoted Spread	Cents	11.29	13.31	8.90	4.41***
Effective Spread	Cents	3.96	4.59	3.22	1.37***
Price Improvement	Cents	7.33	8.72	5.68	3.04***
Trade size	contracts $	5.14	5.21	5.07	0.14**
Trade Price	$	8.15	10.04	5.91	4.13***
Stock Midpoint	$	408.04	530.91	261.32	269.59***
EQ		0.38	0.37	0.38	–0.00**
Market Maker Revenues	Cents	−0.85	−1.63	0.08	–1.71***
Hedge Cost	Cents	4.77	6.16	3.11	3.05***

B: Continuous trading

		All	PFOF	NPFOF	PFOF − NPFOF
Quoted Spread	Cents	9.57	10.74	9.22	1.52***
Effective Spread	Cents	7.47	9.79	6.78	3.00***
Price Improvement	Cents	2.10	0.96	2.44	–1.48***
Trade size	contracts $	4.31	4.14	4.36	–0.22***
Trade Price	$	9.22	10.99	8.71	2.28***
Stock Midpoint	$	398.64	516.51	363.85	152.66***
EQ		0.73	0.90	0.69	0.20***
Market Maker Revenues	Cents	2.55	3.49	2.27	1.22***
Hedge Cost	Cents	4.83	6.15	4.44	1.71***

This table presents average execution costs for trades that execute in the auction (panel A) or continuous trading (panel B), for the option class in the penny pilot program. *PFOF* denotes that the trade is executed at an exchange where the designated market maker pays significant payment for order flow, and NPFOF if otherwise. *Quoted spread* is half the difference of option ask and bid prices prevailing at the time of trade. *Effective spread* is difference between option price and midpoint, multiplied by the trade direction. *Price improvement* is the difference between option quoted spread and effective spread. *EQ* is the ratio of effective and quote spread. *Market maker revenues* is the difference between effective spread and hedge cost. *Hedge cost* is the sum of initial and dynamic hedge cost components. Our sample period is the second half of 2020: August 2020 through December 2020. Spreads are winsorized at the 1% level on each tail. Standard errors are double-clustered at the underlying and day level and are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table A7
Execution costs for top-10 option class

		All	PFOF	NPFOF	PFOF − NPFOF
A: Auctions					
Quoted Spread	Cents	13.40	15.72	9.93	5.79***
Effective Spread	Cents	4.62	5.31	3.59	1.71***
Price Improvement	Cents	8.79	10.41	6.34	4.08***
Trade size	Contracts	4.61	4.66	4.52	0.15*
Trade Price	$	11.87	13.88	8.82	5.06***
Stock Midpoint	$	602.03	743.53	386.10	357.43***
EQ		0.38	0.38	0.39	–0.01***
Market Maker Revenues	Cents	−2.10	−3.06	−0.61	-2.45***
Hedge Cost	Cents	6.65	8.30	4.14	4.16***
B: Continuous trading					
		All	PFOF	NPFOF	PFOF − NPFOF
Quoted Spread	Cents	11.62	14.07	11.01	3.06***
Effective Spread	Cents	8.88	12.76	7.90	4.85***
Price Improvement	Cents	2.74	1.31	3.10	–1.79***
Trade size	Contracts	3.79	3.49	3.87	–0.38***
Trade Price	$	14.46	19.39	13.22	6.18***
Stock Midpoint	$	642.56	951.49	563.50	387.99***
EQ		0.72	0.91	0.68	0.22***
Market Maker Revenues	Cents	1.64	2.18	1.51	0.67**
Hedge Cost	Cents	7.13	10.47	6.29	4.18***

This table presents average execution costs for trades that execute in auction (panel A) or continuous trading (panel B), for the top-10 option class by traded volume. *PFOF* denotes that the trade is executed at an exchange where the designated market maker (DMM) pays significant payment for order flow and NPFOF if otherwise. *Quoted spread* is half the difference of option ask and bid prices prevailing at the time of trade. *Effective spread* is the difference between option price and midpoint, multiplied by the trade direction. *Price improvement* is the difference between option quoted spread and effective spread. *EQ* is the ratio of effective and quote spread. *Market maker revenues* is the difference between effective spread and hedge cost. *Hedge cost* is the sum of initial and dynamic hedge cost components. Our sample period is the second half of 2020: August 2020 through December 2020. Spreads are winsorized at the 1% level on each tail. Standard errors are double-clustered at the option and day level and are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table A8
Execution quality, auctions, and PFOF DMMs for penny pilot program

A: Full sample

	Quoted Spreads	*Effective Spreads*	*Price Improvement*	*EQ*	*MM Rev.*
Auction	2.385***	–2.567***	4.952***	–0.411***	–2.540***
	(0.074)	(0.063)	(0.127)	(0.001)	(0.063)
PFOF	–0.465***	0.719***	–1.183***	0.066***	0.822***
	(0.075)	(0.036)	(0.081)	(0.002)	(0.039)
Auction × *PFOF*	1.755***	–1.657***	3.413***	–0.108***	–1.873***
	(0.148)	(0.078)	(0.208)	(0.002)	(0.091)
DMMP	–0.903***	0.773***	–1.676***	0.168***	0.831***
	(0.040)	(0.022)	(0.043)	(0.001)	(0.023)
|Delta|	30.406***	18.596***	11.810***	0.017***	6.206***
	(1.059)	(0.635)	(0.437)	(0.005)	(0.389)
Gamma	–13.384***	–8.156***	–5.228***	–0.186***	–2.011***
	(0.873)	(0.541)	(0.343)	(0.008)	(0.543)
Vega	18.989***	12.167***	6.821***	–0.008***	6.094***
	(0.662)	(0.418)	(0.257)	(0.001)	(0.415)
Underlying Volatility$_{t-1}$	14.842***	10.616***	4.226***	0.057***	
	(1.564)	(1.088)	(0.486)	(0.004)	
Underlying Quoted Spread	0.348***	0.216***	0.132***	0.000	
	(0.017)	(0.011)	(0.007)	(0.000)	
1/Option Midpoint	1.655***	0.972***	0.684***	0.009***	0.411***
	(0.066)	(0.040)	(0.027)	(0.000)	(0.030)
1/Underlying Midpoint	–79.995***	–44.756***	–35.240***	–0.192	–61.914***
	(22.816)	(14.439)	(8.522)	(0.295)	(14.999)
Underlying MCAP	3.836*	2.939**	0.897	0.006	1.580
	(1.718)	(1.084)	(0.642)	(0.015)	(1.267)
Trade size	–0.060***	0.009	–0.069***	0.003***	0.009
	(0.010)	(0.006)	(0.006)	(0.000)	(0.006)
Call	–1.181***	–0.946***	–0.235***	–0.008***	–0.907***
	(0.082)	(0.052)	(0.033)	(0.001)	(0.062)
Days-to-Expiry	1.884***	1.064***	0.820***	–0.001	0.904***
	(0.120)	(0.074)	(0.048)	(0.001)	(0.080)
Tick Size	0.876***	0.208	0.668***	–0.017***	0.187
	(0.270)	(0.166)	(0.109)	(0.002)	(0.164)
Buy	–0.055***	–0.145***	0.090***	–0.007***	–0.139***
	(0.015)	(0.013)	(0.009)	(0.000)	(0.013)
R^2	0.451	0.395	0.180	0.235	0.151
NObs	74,629,635	74,629,635	74,629,635	74,629,635	74,629,635

(Continued)

Table A8
(Continued)

B: Matched sample

	Quoted Spreads	*Effective Spreads*	*Price Improvement*	*EQ*	*MM Rev.*
Auction	1.520***	–3.109***	4.629***	–0.342***	–3.110***
	(0.090)	(0.102)	(0.172)	(0.002)	(0.108)
PFOF	–1.308***	0.636***	–1.945***	0.170***	0.652***
	(0.087)	(0.049)	(0.086)	(0.002)	(0.051)
Auction × *PFOF*	1.768***	–0.807***	2.575***	–0.183***	–0.885***
	(0.114)	(0.053)	(0.126)	(0.002)	(0.055)
DMMP	–0.293***	0.595***	–0.888***	0.043***	0.596***
	(0.041)	(0.037)	(0.045)	(0.001)	(0.040)
|Delta|	34.166***	20.484***	13.682***	–0.010	5.528***
	(1.313)	(0.834)	(0.521)	(0.005)	(0.499)
Gamma	–17.644***	–10.862***	–6.781***	–0.057***	–1.930***
	(1.397)	(0.847)	(0.580)	(0.009)	(0.751)
Vega	17.692***	12.061***	5.631***	–0.003***	6.313***
	(0.669)	(0.434)	(0.255)	(0.001)	(0.438)
Underlying Volatility$_{t-1}$	14.707***	9.510***	5.197***	0.023***	
	(1.699)	(1.153)	(0.565)	(0.004)	
Underlying Quoted Spread	0.331***	0.200***	0.131***	–0.000	
	(0.020)	(0.012)	(0.008)	(0.000)	
1/Option Midpoint	1.814***	1.062***	0.753***	0.010***	0.417***
	(0.079)	(0.050)	(0.032)	(0.001)	(0.038)
1/Underlying Midpoint	–115.784***	–36.516*	–79.269***	–0.240	–56.520***
	(30.622)	(18.352)	(12.921)	(0.492)	(17.429)
Underlying MCAP	4.014	4.179***	–0.165	0.003	3.051*
	(2.215)	(1.355)	(0.902)	(0.024)	(1.432)
Trade size	–0.133***	–0.004	–0.128***	0.005***	0.031***
	(0.016)	(0.008)	(0.010)	(0.000)	(0.008)
Call	–1.402***	–1.066***	–0.336***	0.006***	–1.102***
	(0.126)	(0.086)	(0.047)	(0.001)	(0.104)
Days-to-Expiry	2.103***	1.010***	1.092***	–0.006***	0.931***
	(0.158)	(0.096)	(0.066)	(0.001)	(0.102)
Tick Size	1.541***	1.274***	0.267**	–0.009***	1.232***
	(0.332)	(0.212)	(0.128)	(0.002)	(0.208)
Buy	0.019	–0.105***	0.124***	–0.005***	–0.093***
	(0.021)	(0.018)	(0.014)	(0.000)	(0.018)
R^2	0.447	0.391	0.200	0.319	0.121
NObs	25,534,362	25,534,362	25,534,362	25,534,362	25,534,362

This table presents regression results for execution quality for the option class in the penny pilot program. *PFOF* is an indicator variable that equals one if the trade is executed at an exchange where the designated market maker pays significant payment for order flow, and zero otherwise. *Auction* is an indicator variable that equals one if the trade is executed at an auction, and zero otherwise. All dependent variables are defined in Table A2. Our sample period is the second half of 2020: August 2020 through December 2020. All specifications include underlying and day fixed effects. Spreads are winsorized at the 1% level on each tail. Standard errors are double-clustered at the option and day level and are reported in parentheses. *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

Table A9
Execution quality, auctions, and PFOF DMMs for top-10 option class

A: Full sample

	Quoted Spreads	*Effective Spreads*	*Price Improvement*	*EQ*	*MM Rev.*
Auction	2.363***	–2.962***	5.325***	–0.393***	–2.908***
	(0.131)	(0.121)	(0.234)	(0.002)	(0.119)
PFOF	–1.165***	1.123***	–2.288***	0.086***	1.304***
	(0.153)	(0.067)	(0.163)	(0.003)	(0.075)
Auction × *PFOF*	2.868***	–2.289***	5.157***	–0.137***	–2.643***
	(0.249)	(0.114)	(0.331)	(0.003)	(0.136)
DMMP	–0.792***	0.877***	–1.670***	0.158***	0.948***
	(0.069)	(0.041)	(0.069)	(0.002)	(0.042)
|Delta|	38.847***	23.300***	15.547***	–0.016	5.509***
	(1.655)	(0.988)	(0.685)	(0.005)	(0.621)
Gamma	–37.058***	–21.501***	–15.556***	–0.148***	–3.408**
	(3.431)	(2.033)	(1.424)	(0.028)	(1.768)
Vega	17.724***	11.364***	6.360***	–0.001***	5.681***
	(0.667)	(0.414)	(0.266)	(0.001)	(0.416)
Underlying Volatility$_{t-1}$	15.561***	11.336***	4.224***	0.063***	
	(2.375)	(1.643)	(0.748)	(0.005)	
Underlying Quoted Spread	0.309***	0.190***	0.119***	0.000	
	(0.018)	(0.012)	(0.007)	(0.000)	
1/Option Midpoint	1.872***	1.058***	0.814***	0.001***	0.405***
	(0.088)	(0.052)	(0.037)	(0.001)	(0.042)
1/Underlying Midpoint	–252.949***	–159.231***	–93.718***	–3.109***	–160.258***
	(65.543)	(41.205)	(24.906)	(0.932)	(39.015)
Underlying MCAP	2.921	2.493	0.428	0.005	1.539
	(2.351)	(1.482)	(0.881)	(0.021)	(1.666)
Trade size	–0.120***	0.012	–0.132***	0.006***	0.052***
	(0.019)	(0.011)	(0.012)	(0.000)	(0.011)
Call	–1.352***	–0.969***	–0.383***	–0.001	–0.956***
	(0.139)	(0.088)	(0.054)	(0.001)	(0.106)
Days-to-Expiry	2.135***	1.107***	1.028***	–0.008***	1.100***
	(0.201)	(0.123)	(0.081)	(0.001)	(0.133)
Tick Size	3.952***	2.150***	1.802***	–0.011***	1.625***
	(0.378)	(0.226)	(0.158)	(0.002)	(0.225)
Buy	0.058**	–0.043**	0.101***	–0.004***	–0.018
	(0.025)	(0.022)	(0.015)	(0.000)	(0.021)
R^2	0.444	0.386	0.184	0.222	0.136
NObs	39,216,478	39,216,478	39,216,478	39,216,478	39,216,478

(Continued)

Table A9
(Continued)

B: Matched sample

	Quoted Spreads	*Effective Spreads*	*Price Improvement*	*EQ*	*MM Rev.*
Auction	1.640***	–3.486***	5.125***	–0.345***	–3.473***
	(0.135)	(0.152)	(0.257)	(0.003)	(0.159)
PFOF	–1.691***	0.665***	–2.356***	0.171***	0.676***
	(0.122)	(0.072)	(0.115)	(0.003)	(0.074)
Auction × *PFOF*	2.357***	–0.942***	3.299***	–0.188***	–1.033***
	(0.168)	(0.079)	(0.183)	(0.003)	(0.081)
DMMP	–0.380***	0.740***	–1.119***	0.050***	0.759***
	(0.057)	(0.055)	(0.060)	(0.002)	(0.060)
|Delta|	40.830***	24.959***	15.870***	–0.033***	5.661***
	(1.743)	(1.086)	(0.713)	(0.006)	(0.656)
Gamma	–43.848***	–25.467***	–18.381***	0.070	–3.505*
	(4.516)	(2.605)	(1.985)	(0.031)	(2.101)
Vega	16.990***	11.786***	5.204***	0.000**	6.236***
	(0.665)	(0.439)	(0.243)	(0.001)	(0.440)
Underlying Volatility$_{t-1}$	15.668***	10.431***	5.237***	0.020***	
	(2.416)	(1.644)	(0.792)	(0.005)	
Underlying Quoted Spread	0.300***	0.185***	0.115***	0.000	
	(0.020)	(0.013)	(0.008)	(0.000)	
1/Option Midpoint	1.907***	1.089***	0.819***	0.004	0.428***
	(0.093)	(0.057)	(0.040)	(0.001)	(0.045)
1/Underlying Midpoint	–379.318**	–265.738**	–113.580*	–3.343	–360.769***
	(166.237)	(107.923)	(64.703)	(2.822)	(113.967)
Underlying MCAP	2.495	3.859**	–1.364	0.005	3.083
	(2.658)	(1.671)	(1.032)	(0.031)	(1.730)
Trade size	–0.190***	–0.025*	–0.166***	0.006***	0.052***
	(0.025)	(0.014)	(0.017)	(0.000)	(0.013)
Call	–1.586***	–1.146***	–0.440***	0.006***	–1.138***
	(0.167)	(0.113)	(0.060)	(0.001)	(0.135)
Days-to-Expiry	2.191***	1.058***	1.133***	–0.008***	1.144***
	(0.220)	(0.136)	(0.090)	(0.001)	(0.147)
Tick Size	4.226***	2.851***	1.375***	–0.007***	2.332***
	(0.408)	(0.259)	(0.162)	(0.002)	(0.262)
Buy	0.090***	–0.029	0.119***	–0.002***	–0.008
	(0.030)	(0.025)	(0.020)	(0.000)	(0.025)
R^2	0.442	0.396	0.176	0.326	0.126
NObs	16,865,168	16,865,168	16,865,168	16,865,168	16,865,168

This table presents regression results for execution quality for the top-10 option class by traded volume. *PFOF* is an indicator variable that equals one if the trade is executed at an exchange where the designated market maker pays significant payment for order flow, and zero otherwise. *Auction* is an indicator variable that equals one if the trade is executed at an auction, and zero otherwise. All dependent variables are defined in Table A2. Our sample period is the second half of 2020: August 2020 through December 2020. All specifications include underlying and day fixed effects. Spreads are winsorized at the 1% level on each tail. Standard errors are double-clustered at the underlying and day level and are reported in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

A2. Routing Choices for Wholesalers on CBOE C1 Options Exchange

In this section, we provide a description of the specific choices for a retail broker and a wholesaler. Using the concrete example of Susquehanna, which purchases roughly 30% of TD Ameritrade's option orders via its subsidiary, Global Execution Brokers LP. Susquehanna pays roughly 35 cents per option contract and four other wholesalers pay about the same amount per contract. Since the PFOF schedule is the same across wholesalers, they compete on order execution quality, including price improvement. After receiving an order, Susquehanna can route it to 1 of 16 exchanges that offer continuous trading and auction facilities with differing fees and trade allocation rules.

The CBOE C1 options exchange uses designated market makers (called DPMs on CBOE C1) to ensure a "fair and orderly market" in their assigned classes.[36] The largest wholesalers also have the most DMM assignments. For instance, Citadel and Susquehanna have over half of all DMM assignments on CBOE for S&P 500 underlyings. The wholesaler can interact with a purchased order by initiating an auction or routing the order to continuous trading at an exchange where the WS is also the DMM.[37] Susquehanna is the DMM on CBOE C1 for Apple Inc. but not for Amazon. When it is routed an Apple option order from TD Ameritrade, it can internalize that order by directing it to the CBOE C1 continuous trading where it has priority or initiate an auction. If it is routed an Amazon order, it cannot easily internalize it in continuous trading and can initiate an auction to interact with the order preferentially. In general, wholesalers pay significantly lower fees to interact with the orders they bring to the market. We outline the details in the following.

Continuous trading (Nonauction)
The wholesaler routes the order to the CBOE C1 platform.

1. **Susquehanna is DPM (Apple):**
   - As the DPM, it has priority at the inside market, meaning it gets a preferential allocation in the order book.
   - If the order is marketable (i.e., it can be executed immediately), it will match against the best available prices in continuous trading, including the wholesaler's quotes.
2. **Susquehanna is not DPM (Amazon):**
   - Susquehanna submits the order to the CBOE C1 platform.
   - Without DPM status, it does not have priority and must compete on a price-time priority basis with other market participants.

Auction

- Susquehanna initiates an automated improvement mechanism (AIM) auction if it seeks to offer price improvement.

AIM Auction Process

1. The order is exposed to the market for a brief period (e.g., 100 milliseconds).
2. Other participants, including the DPM, can submit responses to improve the execution price.
3. If the wholesaler is the DPM, it might match or improve the price offered in the auction.
4. If the wholesaler is not the DPM, it can participate in the auction but must compete with the DPM and other market participants.

Order execution

1. **If price improved in AIM:**

[36] DMMs are referred to as designated primary market makers on the CBOE. As part of maintaining a "fair and orderly market," their most important obligation is to provide quotes 90% of the time during the trading day in their assigned option classes. The CBOE also uses preferred market maker (PMM) and lead market maker (LMM) assignments, which are more flexible and based on market conditions. The obligations and privileges for PMMs and LMMs are similar to those of DMMs, and CBOE usually assigns existing DMMs to these roles.

[37] See panel B of Table 2 for the distribution of DMM assignments by WS across all exchanges.

- The order is executed at the improved price, with the DPM or the best bidder getting the fill.

2. **If not price improved:**

- The order is executed at the best available price in continuous trading.
- **Wholesaler as DPM:**
  - The wholesaler, as DPM, gets a portion of the execution based on its priority status.
- **Wholesaler not as DPM:**
  - The order is filled based on pro-rata priority, where the wholesaler may or may not receive the fill depending on its position in the queue.

A2.1. Auction details

Any CBOE market participant (including WS that are DMMs) can initiate an auction to execute an agency order.[38,39] The auction period is determined on a class-by-class basis and is typically 100 milliseconds.[40] To initiate an auction, the WS can specify an initial price (bid) at which it seeks to execute the purchased order and whether it elects to have allocation priority. If the initiating WS elects to have allocation priority, then it receives 50% (40%) of the agency order if there is interest from one (two or more) other auction participant.[41,42] Alternatively, the WS can initiate an auction by specifying an initial stop price and instruction to auto-match all auction responses up to a specified limit price.[43] The initial stop price cannot be worse than the prevailing national best bid (NBB) or national best offer (NBO). The auto-match feature guarantees the initiating WS allocation equal to the aggregate interest of all auction participants up to a limit price specified by the initiating WS.[44] If an auction fails to produce any price improvement the CBOE auction system executes the agency order at the stop price.[45] The initiating WS is therefore responsible for ensuring that the order executes at a price that is not worse than the NBB or NBO.

Any market participants, other than the initiating WS, can submit responses to an auction.[46] Each response specifies a price and size that the auction participant is willing to execute. WS who are DMMs and initiate the auction are charged a fee ranging from 3 to 23 cents per contract

38 More specifically, any trading permit holder (TPH) can initiate an auction at CBOE. A TPH is a person or organization that has the right to trade at the CBOE. TPHs are subject to fees and exchange regulations. All DMMs are required to be TPHs.

39 CBOE refers to auctions as automated improvement mechanism or AIM auctions.

40 The auction period can be no more than 3 seconds.

41 For an agency order with a size of one contract, the initiating WS receives 100% allocation.

42 The WS receives this allocation at the final auction price.

43 Regardless of how the WS initiates the auction, it cannot modify or cancel an auction after submission. The size specified by the auction initiator must be identical to the size of agency order.

44 The auto-match feature executes the agency order against each price level better than the final auction price, up to the specified limit price. This means that the system will match orders at progressively better prices within this range until the order is fully executed or the limit price is reached.

45 If an auction fails to produce any price improvement and there are multiple bidders, the initiating WS is guaranteed the same allocation as with allocation priority: 50% of the agency order if there is interest from one other auction participant, or 40% of the agency order if there is interest from two or more other auction participants.

46 All auction participants must be trading permit holders at the CBOE and can submit multiple responses, which are aggregated by the auction mechanism at the same price for the same participant.

for winning the auction.[47] Non-DMM initiators are charged 20 cents per contract. Noninitiating DMMs are charged 25 cents per contract for breaking an auction (winning the auction as a noninitiating participant). If the auction is broken by a noninitiating auction participant who is not a DMM, they are charged a fee ranging from 50 to 105 cents per contract. WS therefore have a fee advantage for interacting with purchased orders in auctions at the CBOE if they are also the DMM for the option class. Auction price improvement is determined relative to the prevailing NBB for buy orders and the NBO for sell agency orders at the time the auction is initiated. The minimum price improvement for auctions is 0 or 1 cent depending on the order characteristics.[48]

A2.2. Continuous trading details (Nonauction)

The CBOE uses price and time priority to execute bids and offers, with special allocation priorities for DMMs.[49] WS who are also DMMs on CBOE can leverage their allocation priority to interact with purchased orders. To exercise their priority, WS must have a quote at the NBB or NBO at the time the incoming order is received by the exchange. CBOE classifies orders of five or fewer contracts as “small-size orders”. The WS has priority to execute against the entire size of a small-size order. If the contract size is larger than five-contracts, the WS receives an allocation of 50% if there is one other quote, 40% if there are two other quotes, and 30% if there are three or more other quotes.[50] WS can therefore interact with a substantial allocation of purchased orders in continuous trading as long as they have a quote at the NBB or NBO and there are no existing customer quotes at the time the order is received by the exchange.[51] The CBOE does not use the maker-taker pricing model. Therefore, there are no rebates for providing liquidity through limit orders.

A3. Options versus Equity Market Structure

The market structure of equity and equity options markets differs in several areas, including trading venues, order processing, participant incentives, and regulatory environments. Below, we outline some relevant differences:

Market structure and trading venues

- **Equity markets:** Trades can occur on-exchange or off-exchange, including broker-dealers, wholesalers, or alternative trading systems (ATS). The equity markets are integrated under a national market system, ensuring that trades across different venues are linked and executed at the best available price.
- **Equity options markets:** All trades must occur on a National Market System exchange, as mandated by the SEC, with the Options Clearing Corporation responsible for clearance.

Order types and processing

- **Equity markets:** The primary mechanism is price-time priority, where orders are executed based on price and time of entry. Equity markets typically have tighter spreads due to higher liquidity and trading volumes.

[47] The fee is based on a liquidity provider sliding scale; DMMs who provide higher volume liquidity are charged a lower fee. For instance, a DMM who provides volume in the 0.80% to 1.50% threshold is charged 10 cents, whereas a DMM who provides 2.25% or higher is charged 3 cents.

[48] The auction price improvement must be at least 1 cent better than the NBB or NBO for orders less than 50 contracts and for options that are currently tick constrained, or at the NBB or NBO for larger orders or options that are currently not tick constrained.

[49] In certain cases, the CBOE uses pro-rata allocation for complex orders.

[50] Total allocation cannot exceed the number of contracts quoted by the WS at the best price.

[51] Customer orders have priority over DMMs when priced identically.

- **Equity options markets:** Options markets may use a combination of price-time and pro-rata priority. Options markets generally have wider spreads, reflecting the higher risk and lower liquidity compared to equity markets.

Market maker and participant incentives

- **Equity markets:** Market makers in equity markets provide liquidity and often operate under a maker-taker model, receiving rebates or paying fees depending on whether they add or remove liquidity. Payment for order flow is common, with wholesalers paying brokers to route retail orders to them.
- **Equity options markets:** Market makers in options markets often have designated market maker status, granting them execution priority. PFOF is more significant in options markets due to wider spreads and the need for liquidity. Wholesalers may route orders to exchanges where they hold DMM status to take advantage of these privileges.

Price improvement and auctions

- **Equity markets:** Retail price improvement is usually minimal due to narrow spreads and typically occurs off-exchange or through ATSs. Most trades execute through continuous trading in the order book.
- **Equity options markets:** Price improvement primarily occurs through on-exchange auctions. These auctions allow market participants to offer better prices than those in the order book and are a crucial feature of options trading.

Regulatory and execution differences

- **Equity markets:** Regulated under Regulation NMS, which mandates the best execution across linked markets. Equity markets have strict rules on trade-throughs, ensuring trades are executed at the best available prices.
- **Equity options markets:** All trades must occur on regulated NMS exchanges, with the SEC overseeing the market structure. Options market rules vary more across exchanges, particularly concerning DMM priorities and auction structures, making the market more complex.

All trades for standard options contracts must be executed on an options exchange to be cleared by the Options Clearing Corporation, the primary clearinghouse for U.S. equity options. To interact with purchased retail orders, wholesalers must submit all orders to an options exchange. At an options exchange, WS can interact with purchased orders by initiating an auction or executing the order in continuous trading. Appendix Section A2 provides a detailed description of these routing choices and the resulting allocation at the CBOE Option exchange. On-exchange internalization in options contrasts with the current equity market structure, where wholesalers can interact with marketable retail equity orders off-exchange.[52] By executing retail orders off-exchange, WS can interact with the entire size of the purchased retail equity order. As highlighted in Appendix Section A2, the options market structure generally allows WS to interact with the entire size for "small-size orders" or when there are no competing bids or quotes. Proposed Rule 615 of Regulation NMS, entitled the "Order Competition Rule," aims to change the current equity market structure by requiring that retail orders be exposed to competition through on-exchange auctions, similar to the current option auctions. The proposed regulation implies that wholesalers will only be guaranteed to interact with the entire size of the purchased retail equity order when there are no competing bidders.

52 While WS can also interact with purchased orders in exchange retail liquidity programs, these account for only 5% of equity retail volume Ernst, Sun, and Spatt (2023).

A second important difference between the equity and options markets is the price increment available to wholesalers. While Rule 612, which specifies a minimum pricing increment, prohibits the display of quotes in fractional cents, it allows equity orders to execute at prices in fractional cents. Wholesalers can therefore manage their execution quality in stocks at a more granular level without initiating auctions. In contrast, options prices are quoted in ticks, which are generally 5 or 10 cents wide, while option auctions have a 1-cent minimum price increment.[53] Consequently, while wholesalers can use auctions to more finely manage execution quality for option retail orders, they are able to achieve this for equity retail orders without the need for auctions in the current equity market structure.

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