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Abstract

Cross-asset market activity can be a channel through which illiquidity risks originating in one market can propagate to others. This paper examines the complex intra-day linkages between the U.S. equity securities market and the equity derivatives market using high-frequency data on S&P 500 index exchange-traded funds and E-mini futures contracts. The paper finds a positive, but short-lived, relationship between the two markets' order flow activities, which relates to the supply, demand, and withdrawal of liquidity between the two markets. The paper also finds that cross-asset market order flow is a key component of liquidity and price discovery, particularly during periods of market volatility.

Keywords: cross-market arbitrage, order flow, liquidity, market structure, automated markets

JEL Classification Numbers: G12, G13, G14

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Financial markets provide two important functions for asset pricing: liquidity and price discovery (O'Hara (2003)). As technical innovations in financial systems and markets have allowed for automation, market participants' trading capacity and access to substitute assets have expanded (Jain (2005); Hendershott and Moulton (2011); Angel et al. (2011)). These changes have allowed market participants to trade between similar asset markets when implementing investment and hedging strategies, further interconnecting the pricing process of similar products and contributing to liquidity (Hendershott et al. (2011)).

While these changes have perhaps benefited the most actively traded assets, they may have inhibited effective liquidity provision for smaller asset classes (Mnuchin and Phillips (2017)). Additionally, the increase in automation and cross-asset trading has made it more difficult to determine the liquidity of any one asset, particularly during periods of market uncertainty and volatility (Nagel (2012); Holden and Jacobsen (2014)). For example, the Securities and Exchange Commission (SEC) and Commodity Futures Trading Commission (2010) report on the May 6, 2010, flash crash and SEC (2015) research note on August 24, 2015, show how cross-asset market activity can be a channel through which illiquidty risks originating in one asset market can propagate to other securities markets. Both events raise concerns about the stability of capital markets and highlight the need to assess the complex linkages among markets, factors that could cause "flash events" to propagate across markets (Financial Stability Oversight Council (2018)).

In this paper, we use high-frequency intra-day order flow data from exchange-traded funds (ETF) and futures markets to study their effects on one another's liquidity and price discovery. We study these assets and their relationship for two reasons. First these securities play an increasingly important role in determining financial asset valuations. To give some perspective, consider the S&P 500 Equity Index, a bellwether of financial market performance, which covers 80% of U.S. market capitalization and is valued at $24 trillion.[1] Though the index is a composite of 500 equities, a large portion of the trading activity and evaluation is done through ETFs, futures, options, and other investment vehicles. In 2018, the dollar volume of trading of the S&P 500 Equity Index's equity constituents was $31 trillion, whereas E-mini S&P 500 futures contract saw $60 trillion and the SPDR S&P 500 ETF saw $6.6 trillion in volume. In addition, Ben-David et al. (2018) highlight the increasing popularity of ETF trading in financial markets, accounting for about 35% of the

[1]Market capitalization as of April 30, 2019.

volume of U.S. equity markets.

Second, as ETF and futures liquidity and price formation are influenced by both asset markets, understanding how order flow within and across markets contributes to the formation of prices collectively is critical to determining the potential for idiosyncratic asset events creating cross-asset spillovers in liquidity and volatility. As similar assets may be arbitraged; there is the potential for creating layers of demand shocks. Ben-David et al. (2018) find that though increased access to intra-day liquidity and diversification is generally beneficial, as in the case of ETFs, assets that incorporate typically risky strategies can create sudden demand shocks and volatility in their underlying. Similarly, Stein (1987) argues that speculation in futures markets can act as a vehicle for price destabilization and reduce welfare in other markets.

We complement these works by investigating the relation between ETFs and futures as additional sources of volatility and fragility of the equity capital market financial system. We examine cross-asset market order flow from two tightly interconnected and consequential assets linked by the S&P 500 equities index, the front month E-mini S&P 500 futures contract and the SPDR S&P 500 ETF. By employing these data, we look to demonstrate whether a co-movement of order flow between the two assets exists, and whether this supports or dampens the cross-asset market pricing processes.

Primarily, we are interested in determining how order flow characteristics, representing the direction of trade activity, and the supply, demand, and withdrawal of liquidity, can be employed to understand the price formation process. For example, is price formed in one asset and arbitraged in the other? Or are transactions split across both assets to access liquidity directly? We answer these questions, and more, by considering not just how cross-asset market prices are correlated, but also how order flow features and bid-ask spreads influence the pricing process.

Secondly, we are concerned with cross-asset order flow activities during periods of excess volatility, where we see reduced liquidity and the dislocation of cross-asset price parity. Though it is not unusual for markets to suffer short periods of illiquidity or price dislocation, markets normally self-heal rapidly. However, in extreme cases markets can amplify and reinforce price changes, leading to unstable feedback pricing (Bouchaud (2011)), as was the case in the May 6, 2010, flash crash. We examine the 10 most volatile days between 2014 and 2017, and compare them to the same day one year prior, to see how the two assets behave during such periods.

Cross-asset and multi-market analysis of interconnected assets has been of significant interest to academics (Chan et al. (1991); Ellul (2006); Baruch et al. (2007); Yang et al. (2012); Halling et al. (2013)) and regulators (The Brady Commission (1988); Report to the Board of Directors of the New York Stock Exchange (1990)) long before the advent of high-speed optical fiber and microwave connections. For example, Chan et al. (1991) point out that the interdependence between cash and futures markets in both directions is useful to understand persistence and predictability of returns and volatility, although they do not consider the relations between the markets at the order flow level.

Kondor (2009) models arbitrageurs' convergence trading activity, which reduces price discrepancies, but also notes that arbitrageurs can generate losses with positive probability. Moreover, prices can converge or diverge and affect liquidity even if arbitrageurs' capital constraints are not binding. Again, order flow analysis can add a previously unknown dimension to this puzzle because in a single-market context, Brogaard et al. (2014) show that order flow affects price formation.

This paper makes three main contributions. First, it links order flow dependence to cross-asset order flow by examining the existence of a strong contemporaneous co-movement in order flow in ETF and futures markets. Contemporaneous interconnectedness is particularly strong for liquidity demanding orders in volatile periods. However, unlike with contemporaneous cross-asset order flow, we generally do not find any long-term persistence or spillover in illiquidity risks across markets. However, we do find short term feedback from lagged futures market to the ETF market, especially in volatile periods.

When examining buy- versus sell-driven order flow, used to test if market participants engage in cross-asset arbitrage versus accumulation, evidence suggests the latter at a contemporaneous level. In other words, an increase in selling of the ETF market goes along with increased selling in the futures market. Our findings are comforting because cross-asset risk accumulation is short lived, with no evidence of persistence or build-up over time.

Second, we contribute to understanding how liquidity is accessed across the ETF and futures markets. We find that the liquidity of both assets, measured by bid-ask spreads, is highly dependent on cross-asset order flows. These effects are stronger in the futures market than the ETF market, and during volatile periods than during the benchmark ones. We find no evidence for illiquidity spillovers build-up during such periods.

Third, our work contributes to the expanding mircostructure literature that uses order flow data to explain asset price formation and price discovery (Brogaard et al. (2014); Hirschey (2018)). We find that cross-asset market order flow is a key component to price discovery, with several features of one asset's order flow significantly influencing the other's price during periods of market volatility. Additionally, we test the impact of order flow on price correlation. We find that higher cross-asset price correlation is associated with higher volume, liquidity demand, and message traffic in both ETF and futures. However increased liquidity supply within a market or across markets reduces price correlation. After controlling for all variables together, we find that an increase in liquidity supply activity in one market weakens its price integration with the other market in volatile periods. As each asset's price is interdependent, any deviations can create excess volatility as the two markets reconcile their valuations.

In Section 1, we summarize the data and order flow variables used to examine the behavior of liquidity. In Section 2, we empirically examine how order flow activity is cross-asset market dependent by studying the supply, demand, and withdrawal of orders. In Section 3 we examine how cross-market order flow activity leads to market liquidity spillover, observed in each assets bid-ask spread. In Section 4 we examine how the cross-market dependent order flow can influence the stability of the price discovery process during periods of volatility. Finally, in Section 5 we examine how cross-asset market trading may cause fragility using two case studies. Conclusions follow in Section 6.

1 Data and Order Flow Statistics

In this paper, we employ cash traded ETFs and futures markets data from a set of publicly available pre- and post-trade product data sets, made available through Thesys Technologies. In the case of the cash equities and ETF market, we use data similar to the SEC's Market Information Data Analytics System (MIDAS) and the New York Stock Exchange Inc. Trade and Quote (TAQ) databases with trade ticker and market depth files, which provide detailed information on all trades and non-hidden orders resting across 13 public exchange order books. For futures, the data format is similar to the Market Depth FIX data from the CME Group.[2]

[2]To make the data comparable, we transform the futures limit order book level message data to inferred individual order messages, to the extent possible.

As order flow represents the activities associated with pricing and transacting an asset in electronic limit order book markets, we are interested in examining how two tightly coupled and substitutable assets' order flows influence one another. For our study we select asset pairs linked to the S&P 500 equities index, the SPDR S&P 500 ETF and front month E-mini S&P 500 futures contract, based on their relative importance for the financial market system. Figure 1 plots the intraday price pattern for the SPDR S&P 500 ETF (ticker symbol SPY) and E-mini S&P 500 futures (ticker symbol ES) in panel A during a typical market open and in panel B during a high-volatility day. Panel A shows how the two assets have tight bid-ask spreads of one tick and that the products move in tandem with one another. In contrast in panel B, we see that both the spreads of the two products widen and the integration of their prices dampens as their prices move semi-independent of one another.

[**Figure 1: Bid-Ask Spreads of S&P 500 ETF and Futures**]

These assets' prices are kept in lock step with one another through a mixture of market participants selecting to subdivide their activities across the two assets based on price and liquidity, so as to lower transaction costs, and arbitrageurs looking to profit from closing price differences (Ellul (2006)). Figure 2 provides an example of these two mechanisms. On the left panel, the buyer and seller equally distribute their orders to minimize the possibility of a price differential occurring, represented by the dashed line. On the right panel, the buyer and seller's transactions are kept independent, but the arbitrageur keeps the two assets prices in sync through buying and selling in the two assets at some profit.

[**Figure 2: Example of Cross-Asset Market Trading**]

However, as Figure 1 panel B shows, these two mechanisms are not perfect, leading to prices of the two assets falling out of step. Figure 3 provides two examples of how the activities of substitution and arbitrage can lead to longer-term pricing discrepancies. A breakdown in substitution can occur due to the preference by buyers and sellers for one asset or due to the market of an asset closing. Similarly, if the arbitrageur were to suffer either a malfunction or the inability to offset their orders, their activity would not be able to inform pricing in ES and could cause liquidity to dry up during extreme volatility like that on May 6, 2010, or August 24, 2015.

[**Figure 3: Example of Cross-Asset Market Trading and Price Dislocation**]

1.1 Order Flow Variables

To measure activities from order flow data, we construct a series of variables that are meant to capture different aspects of demand and supply for contracts in a limit order book. To interpret the direction of demand and supply, we build an order flow imbalance metric based on prior literature. To interpret how order flow influences the dynamics of supply and demand we build three metrics - liquidity demand, liquidity supply, and liquidity withdrawal - meant to help explain changes in bid-ask spreads and the interconnectedness of asset prices. We construct these measures of order flow using trades, new orders, and order cancellations, based on time frequencies of 1 second (s) and 10 milliseconds (ms).[3] In the following subsections we cover the exact construction of these variables.

1.1.1 Order Imbalance

We define order imbalance to be the proportion of new buy orders divided by the total number of new orders, as in equation (1). When buy orders in one market are offset by sell orders in that market, the order imbalance averages 50 percent in stable markets. When buyers are more aggressive, the ratio is above 50 percent and when sellers are more aggressive the ratio is below 50 percent.

$$\text{Order Imbalance} = \frac{\#\text{New Buy Orders}}{\#\text{New Buy and Sell Orders}} \tag{1}$$

Following from Ellul (2006), we employ a cross-asset market correlation of the change in order imbalance to evaluate market participant behavior. When a negative correlation occurs, due to buying (selling) ETFs and selling (buying) futures, we interpret this activity as cross-asset arbitrage. Cross-asset arbitrage should help to mitigate or offset the large volumes in one market by

[3] We select the 10 millisecond interval as it is roughly the round trip speed of transacting between the two trading locations of our assets, SPY in New York City and ES in Chicago.

counterbalancing activity at another, thus reducing price divergences. In contrast, when market participants engage in simultaneous buying or selling ETFs and futures, such causing correlations to be positive, it may indicate a build-up in the aggregate activity crossing markets and the spreading of potential risks.

1.1.2 Liquidity Demand

To measure liquidity demand pressures we use the proportion of trade messages to total message traffic, as in equation (2). A trade is often a result of an aggressive decision to buy at the higher offer price or sell at the lower bid price. Extremely aggressive trading behavior can potentially stress a market and make it illiquid for subsequent participants. Examining whether this metric is cross-asset market dependent, can provide insight into whether the illiquidity in one market can spill over to another market, thereby making the both markets illiquid.

$$\text{Liquidity Demand} = \frac{\#\text{Trade Messages}}{\#\text{Message Traffic}} \tag{2}$$

1.1.3 Liquidity Supply

Systemic illiquidity can also result from the lack of new liquidity supply. We measure liquidity supply with the proportion of new order messages to the total number of messages, as in equation (3). Both buy and sell side orders that become part of the standing limit order book for the security are included in the numerator. The denominator is the total message traffic.

$$\text{Liquidity Supply} = \frac{\#\text{New Limit Order Messages}}{\#\text{Message Traffic}} \tag{3}$$

1.1.4 Liquidity Withdrawals

Finally, liquidity suppliers have the option to withdraw previously committed liquidity by cancelling their orders. We measure the rate of liquidity withdrawal with the proportion of cancel messages to the total number of messages, as in equation (4). The sudden withdrawal of liquidity in one markets can spook participants and cause them to search for new liquidity in other markets.

$$\text{Liquidity Withdrawal} = \frac{\#\text{Cancel Order Messages}}{\#\text{Message Traffic}} \tag{4}$$

1.2 Empirical Summary of Order Flow Statistics

We run several tests over a sample of 20 periods.[4] The periods comprise the 10 highest-volatility days and 10 matched neutral-volatility benchmark days between 2014 and 2017 to compute baseline statistics. The benchmark periods are matching days from the same month of the year, on the same day of the week, one year prior the high-volatility days. The entire sample of 553.73 million messages across ETF and futures markets from 20 periods between 2014 and 2017 is drawn in Table 1. All variables are averaged or aggregated for every 10ms between the trading hours of 9:30AM and 4:00 PM EST.

[**Table 1: Intraday Transaction Statistics**]

In Table 1, panel A presents the baseline (benchmark) descriptive statistics for both the ETF and futures markets in terms of intra-day returns, spreads, order imbalance (proportion of buy orders), message traffic, liquidity supply in form of new orders added to the limit order book, liquidity demand (resulting in trades), and liquidity withdrawal (cancellations). We calculate the mean value for each variable by averaging the 553.73 million messages across the 23.4 million 10ms intervals in 10 trading days, in their respective categories.

The average trading volume over 10ms intervals is 37 SPY shares and 0.59 ES contracts in the baseline period. Volume almost doubles to 79 SPY shares and 0.97 ES contracts in the volatile periods shown in Panel B. There is significant variation in the level of activity. The median of 0 shares/contracts implies that not all of the 23.4 million 10ms periods in the sample used in Table 1 have activity. Of these periods, 53 percent of volatile and 37 percent of benchmark SPY bucket have some order flow, whereas 35 percent of volatile and 22 percent of the benchmark ES buckets have order flow.[5]

[4] See Table A.1 for list of dates.

[5] When we aggregate the order flow into 1s intervals, more than 99.5 percent of the seconds have order flow activity for both SPY and ES in benchmark and volatile samples. Although the choice of window is merely a scaling factor for the descriptive statistics in Table 1, it represents a trade-off between better response speed and more data exclusion because of missing lagged values with the 10ms windows when conducting lead-lag analysis. Thus, we present the results of the analysis with both 1s and 10ms aggregations.

In examining our variables of interest, we find that order imbalance, buyer- and seller-initiated orders are almost evenly split at 50 percent on the benchmark dates for both SPY and ES. However, the proportion of buy order drops somewhat on volatile days for SPY to 48.7 percent.

Liquidity supplying orders represent just slightly over half of all messages, between 51 to 54 percent, in the SPY and ES order books. In contrast, liquidity demanding messages constitute only 1 percent of the SPY messages and 3.6 percent of the the ES messages in the benchmark period. The proportion of messages representing trades jumps to 2.1 percent in the volatile period for SPY but is unchanged for ES. Liquidity withdrawal through cancellation of previously submitted limit orders is a significant proportion of message traffic, accounting for 45.7 percent of SPY messages and 37.2 percent of ES messages. SPY order cancellations decrease by more than 5 percentage points to 40.6 percent in volatile periods, indicating that many orders at prices near the National Best Bid and Offer (NBBO) are quickly executed before they can be revised or canceled.

Finally, Table 1 presents bid-ask spreads in each market, as a measure of each market's liquidity. The average and median ticks are near if not at the minimum tick size (one tick) in both panels. However, at the extremes, when we compare panel A's maximum spreads of 7 ticks for SPY and 6 ticks for ES, to those observed in panel B, we see a significant jump to 105 and 24 respectively. This extreme widening suggests that both markets saw significant drops in liquidity during these periods, though they have not occurred simultaneously.

We see a similar pattern when looking at returns. The returns at 10ms for SPY have an average and median of 0 when rounded to three places after the decimal, although they range from -4.5 to +5 basis points in the benchmark period. The return at 10ms for ES also has an average and median of 0, with a wider range from -7.41 to +6.16 basis points in the benchmark period. In panel B, the average and median returns remain 0, but the range expands by more than 10 times for the ETF market and almost 5 times for the futures market.

2 Cross-Asset Market Order Flow

Academic studies have focused on cross-asset market price and returns behavior (MacKinlay and Ramaswamy (1988); Chan et al. (1991); Budish et al. (2015)). However, no studies to the best of the authors' knowledge have focused on how intra-day order flow keeps cross-asset prices conintegrated and arbitrage-free. As a result, an important first step in our analysis is to demonstrate how order flow between our two assets is cross-market dependent. For example, can we detect whether there exists arbitrage or split transaction order flow activity occurring across both assets?

In the following section we examine order flow relationships between our two assets by calculating correlation statistics and running a structural vector autoregression (SVAR) over each of the four order flow variables. The relatively simple cross-asset contemporaneous and lead-lag correlation measures the degree to which the ETF and futures markets move in tandem. The SVAR specification allows us to understand the Granger causality between the two markets while controlling for autocorrelations within a market that may be caused by fundamental factors.

In Table 2, we report the cross-asset correlations. All variables are aggregated in 1s intervals in panel A and 10ms intervals in panel B. For the changes in order imbalance, we observe positive cross-asset correlations in both the benchmark and volatile periods. Thus, we do not see any evidence of contemporaneous arbitrage across markets where a sell order in one market is instantaneously offset by a buy order in another market. The activities of market participants in ETF and futures asset markets appear to build up the aggregated level of contemporaneous cross-asset risk through substitution.

[**Table 2: Cross-Asset Market Time-Series Correlations**]

Next, we assess the persistence and spillover of this risk build-up by studying the lead-lag correlation coefficients. At the 1s intervals, we find that both the lead and lag correlations are negative, indicating a lack of feedback and an absence of further build-up of cross-asset risks based on 1s lagged information from the other market. Beyond the 1s interval, the economic significance of correlation coefficients is very small.

In the next three columns, we assess the cross-asset interconnectedness in the state of liquidity. The contemporaneous change in liquidity supply is again positively correlated across markets at both 1s and 10ms frequencies for both the benchmark and volatile periods. Thus, ETF and futures markets are interconnected through contemporaneous liquidity supply of buy and sell orders that are added to each limit order book. At the 1s interval, both lead and lag negative correlations indicate a lack of feedback and an absence of any illiquidity spillover across markets. Results are similar for the 10ms intervals, though we observe some feedback from futures to ETF in the volatile periods. Beyond the 1s interval, the economic significance of correlation coefficients is very small.

The contemporaneous change in liquidity-demanding trades is again positively correlated across ETF and futures markets at the 1s intervals. Notably, the correlation increases significantly during the volatile periods relative to the benchmark period. Thus, the aggregate effects of traders who demand liquidity in periods of volatility is amplified through cross-asset market effects. However, for the shorter 10ms periods, the correlation does not increase, indicating slower cross-asset market reaction times for actual trades relative to the benchmark period. The positive lead correlations indicate spillover of aggressive trading from ETF to futures. However, these effects are short-lived and the economic significance of correlation coefficients is very small.

In the last column of Table 2 we examine order cancellations. Excessive order cancellations make it particularly difficult for market participants to understand the true amount of liquidity available in the market and thus have received regulatory attention. The contemporaneous correlation of order cancellation in ETF and futures is positive at the 1s interval and negative at the 10ms interval, but the economic magnitude of both cancellation correlation coefficients is small.

To interpret the order flow relationships as causal we next construct a SVAR model which allows us to assign Granger causality to each lagged order flow component. The SVAR analysis isolates the dynamic relations between contemporaneous cross-asset order flow activity while controlling for autocorrelations within a market that may be caused by fundamental factors. The SVAR thus allows us to incorporate the change in order imbalance (OI), liquidity supply (LS), liquidity demand (LD) and liquidity withdrawal (LW) activity for both SPY and ES. The SVAR equations are as follows:

$$\Delta \text{OI}_t^{\text{spy}} = \sum_{i=1}^{6} \beta_{1,i} \Delta \text{OI}_{t-i}^{\text{spy}} + \sum_{i=0}^{6} \beta_{1,7+i} \Delta \text{OI}_{t-i}^{\text{es}} + \epsilon_t, \quad \Delta \text{OI}_t^{\text{es}} = \sum_{i=1}^{6} \beta_{2,i} \Delta \text{OI}_{t-i}^{\text{spy}} + \sum_{i=1}^{6} \beta_{2,7+i} \Delta \text{OI}_{t-i}^{\text{es}} + \epsilon_t; \tag{5}$$

$$\Delta \text{LS}_t^{\text{spy}} = \sum_{i=1}^{6} \beta_{1,i} \Delta \text{LS}_{t-i}^{\text{spy}} + \sum_{i=0}^{6} \beta_{1,7+i} \Delta \text{LS}_{t-i}^{\text{es}} + \epsilon_t, \quad \Delta \text{LS}_t^{\text{es}} = \sum_{i=1}^{6} \beta_{2,i} \Delta \text{LS}_{t-i}^{\text{spy}} + \sum_{i=1}^{6} \beta_{2,7+i} \Delta \text{LS}_{t-i}^{\text{es}} + \epsilon_t; \tag{6}$$

$$\Delta \text{LD}_t^{\text{spy}} = \sum_{i=1}^{6} \beta_{1,i} \Delta \text{LD}_{t-i}^{\text{spy}} + \sum_{i=0}^{6} \beta_{1,7+i} \Delta \text{LD}_{t-i}^{\text{es}} + \epsilon_t, \quad \Delta \text{LD}_t^{\text{es}} = \sum_{i=1}^{6} \beta_{2,i} \Delta \text{LD}_{t-i}^{\text{spy}} + \sum_{i=1}^{6} \beta_{2,7+i} \Delta \text{LD}_{t-i}^{\text{es}} + \epsilon_t; \tag{7}$$

$$\Delta \text{LW}_t^{\text{spy}} = \sum_{i=1}^{6} \beta_{1,i} \Delta \text{LW}_{t-i}^{\text{spy}} + \sum_{i=0}^{6} \beta_{1,7+i} \Delta \text{LW}_{t-i}^{\text{es}} + \epsilon_t, \quad \Delta \text{LW}_t^{\text{es}} = \sum_{i=1}^{6} \beta_{2,i} \Delta \text{LW}_{t-i}^{\text{spy}} + \sum_{i=1}^{6} \beta_{2,7+i} \Delta \text{LW}_{t-i}^{\text{es}} + \epsilon_t, \tag{8}$$

where, the ETF equations, betas 1 to 6 capture the autocorrelation coefficient for the within-ETF market lagged order flow, beta 7 is the coefficient for the contemporaneous cross-market futures order flow, and betas 8 to 13 capture the coefficients for lagged futures order flow. The futures market equations are analogous except that they only have lagged coefficients for futures market and cross-market ETF order flow.[6]

In Table 3, we present the regression estimates of cross-asset market interconnectedness, by including the lagged within-market autocorrelation for our four measures as control variables. As before, order flow is aggregated at 1s intervals in panel A and 10ms intervals in panel B and each panel allows us examine contemporaneous cross-market interconnectedness as well as lead-lag relations.

[**Table 3: Cross-Asset Market Order Flow SVAR**]

Focusing first on order imbalance in Table 3, we observe that the contemporaneous cross-asset market regression coefficients are positive in both panels A and B for both volatile and benchmark periods, confirming the contemporaneous interconnectedness correlation results previously presented in Table 2. Thus, contemporaneous cross-asset market aggregate risk in the two markets combined is higher. Thus, cross-market activity is neither independent nor offset by instantaneous arbitrage.

The next relevant question is for how long does the activity in one market affect the other? The cross-asset market lagged effects vary depending on the market. In the case of the S&P 500 ETF market, the coefficient for all lags of the futures market are negative, in both the benchmark and volatile periods, and in the 1s and 10ms time aggregations. These results again indicate a lack of feedback over time and absence of any further build-up of cross-asset market spillover in the direction from futures to the ETF market beyond the contemporaneous time frame. However, in the futures regression equation, the coefficients for lagged ETF market activity are positive for at least two lags in all regressions and all six one-second lags during the volatile period. Thus, the lagged change in ETF market order imbalance is followed by a similar change in futures market order imbalance. The futures markets appear to amplify the risks from skewed ETF market order

[6] Following from Chan et al. (1991) and the observed correlation analysis performed on the order flow, we model the contemporaneous effect of the future influencing the ETF.

imbalances.

Autocorrelation coefficients, which control for the within-market lagged effects, are negative in both time aggregation panels for the order imbalance in the first panel and all other liquidity variables in the remaining panels for the baseline and volatile periods. This result suggests that within-market momentum is not resulting in any risk build-up over time. Instead the negative autocorrelation point to quick within-market risk mitigation.

Next we focus on SVARs for liquidity variables, in the remaining panels of Table 3, to assess both contemporaneous the persistence of lagged cross-asset market interconnectedness and risk spillover for the three aspects of order flow liquidity controlling for within-market autocorrelation in each market. First in examining liquidity supply, we find the contemporaneous cross-asset market coefficient is positive, and statistically significant for the benchmark and volatile periods in both panels. Thus, there is evidence of contemporaneous interconnectedness and contemporaneous risk build-up for ETF and future market illiquidity. Several of the lagged cross-asset market coefficients in the liquidity supply regression are positive in the first column, signifying some amplification of illiquidity risk in the direction from futures to ETF. However, in the futures regression, the lagged cross-asset market coefficients are negative, indicating risk mitigation. In other words, changes in liquidity supply do not amplify in the direction from ETF to futures over time.

Second, in examining cross-asset market liquidity demand to understand whether the illiquidity risk arising from aggressive trading is being enhanced or mitigated across markets. The cross-asset market lagged effects vary depending on asset. For the ETF market, the statistically significant negative coefficients for all lagged futures activity in both benchmark and volatile period for the panel lags indicates that illiquidity risk is being mitigated in the direction from futures to ETF markets. In the case of the futures market the results are mixed. The coefficients are statistically significant and generally positive for lagged ETF market activity in both panels, except for four lags in benchmark period of 10ms lags where the coefficients are negative. This indicates that during volatile periods, illiquidity risk is being mitigated in the direction of ETF to futures markets.

Finally, in examining cross-asset liquidity withdrawal, we observe generally mixed results. The contemporaneous cross-asset market regression coefficients are positive for the 1s interval in benchmark periods, indicating interconnectedness. Although the coefficients for the volatile period are positive for the 10ms panel, they are negative in the 1s panel. Similarly, the signs for lagged cross-asset market cancellation activity are mixed depending on the time interval.

Overall, the balance of evidence in Tables 3 does not point to persistence of cross-asset market illiquidity spillover. However, more generally we do find a strong contemporaneous interdependence between the two market's order flows, suggesting the presence of cross-asset trading.

3 Cross-Asset Market Liquidity

As the previous section demonstrates, order flow between the ETF and future does appear to have a contemporaneous cross-asset dependence, likely due to automated cross-asset trading. As both Nagel (2012) and Holden and Jacobsen (2014) discuss, automation has made it more difficult to determine the liquidity of any one asset, particularly during periods of market uncertainty and volatility. Establishment of microwave technology for message relay between Chicago and New York also indicate that liquidity suppliers and demanders have the ability to observe and react to cross-asset order flow. In this section we examine how cross-asset order flow dependence matriculates to influence liquidity in each of the two assets. Bid-ask spread is a primary measure of available market liquidity (Stoll (2000)). We examine how order flow activity and bid-ask spread interact.

As Stoll's (2000) address highlights, order flow is a determinant of bid-ask spread. In this section we extend the literature by investigating how liquidity is affected by not only by within-market order flow but also cross-asset market order flow. We are specifically interested in determining whether cross-market interdependent order flow activity can lead to market illiquidity spillovers. This is important because if the liquidity of ETF and futures markets varies over time in a related way, and if this relationship is ignored in tests of lead and lag relations in price and volumes, specification error can lead to incorrect expectation of the liquidity available in either market.

First we investigate different levels of spread, followed by changes in spread in the following tables. In Table 4.A, we examine the impact of within market activity on future liquidity (spreads) and also the impact of current spread on the future order flow within the market. We divide the sample into two groups based on the size of the bid-ask spreads, as measured in the number of ticks.[7]

The data represents two panels for the ETF and futures markets, respectively, representing the

[7]A tick is defined as the minimum upward or downward movement in the price of an asset on a limit order book.

order flow's impact on bid-ask spread (pre-activity) and the bid-ask spread's impact on order flow (post activity) at 1s. We do so to try to understand how order flow and spread are interdependent. The first column of the table indicates the size of spread in number of ticks, wth 1 tick representing the most liquidity market and 2+ ticks representing illiquid markets. For each activity section, we present columns labeled new order, trade, cancel, and OI, which map to the liquidity supply, liquidity demand, liquidity withdrawal and order imbalance variables, respectively. Positive values in the difference row indicate that the variable causes illiquidity and negative differences indicate that the variable improves liquidity.

[**Table 4.A-B: Spread and Order Flow**]

For example at the 1s aggregation, we find that the proportion of new order supply decreases and trades increases when spreads are wider than 1 tick. These changes in order flow are consistent with the interpretation that both the ETF and future see declines in liquidity supplying order flow and increased in order flow prior to declines in each assets liquidity.

The impact of liquidity deterioration at the 10ms frequency is similar to the 1s results presented above. Also, in the post-activity window wider spreads are associated with lower subsequent liquidity supply and higher subsequent liquidity demand.

In Table 4.B, we study the cross-asset market effects of ETF market pre-activity on futures spreads and how futures spreads affect subsequent ETF market activity. As before, we divide the sample into two groups based on the size of the bid-ask spreads measured in the number of ticks but the order flow activity is now cross-market with ETF spreads matched up futures order flow activity and vice-versa.

In Table 4.B a negative difference in liquidity supplying cross-market orders suggest that they improve cross-market liquidity at 1s frequency and a positive difference for liquidity-demanding cross-market trades suggest that they make cross-markets illiquid at all frequencies.

To further understand the association between liquidity and cross-asset market activity, we examine changes in spreads. Table 5.A presents the within-market relation between spread changes and order flow in the period immediately preceding the spread changes. In 1s and 10ms panels we test whether the changes in order flow activity in the previous time unit caused changes in market spreads and by what magnitude.

[Table 5.A-B: Spread Change and Order Flow]

For both ETF and futures markets, we observe a non-linear U-shaped relation between spread changes and within-market order flow activity. In other words, spread increases and spread decreases are preceded by a similar change in order flow activity. Spreads increases and decreases are both preceded by a significant jump in liquidity-demanding trade messages, number of total messages, and trading volume. Spreads increases and decreases are both preceded by a drop in liquidity-supplying orders added to or cancelled from the limit order books. Order imbalance statistics fluctuate a lot, presenting a noisy picture about its relationship with spread.

In Table 5.B, we tabulate the cross-asset market spread change and order flow variables. We again observe a non-linear U-shaped relation between spread changes and cross-asset market order flow activity. In other words, spread increases and spread decreases are preceded by less liquidity supply and more liquidity demand. However, the frequency column shows that for most of the day (nearly 98 percent of the time) there is no change in spread.

In order to interpret how the dynamics of order flow influence liquidity, both within and across markets, we construct an SVAR that incorporates the order flow variables and the spread of each asset. The dependent variables in the SVAR, presented in equation (9), are the two asset bid-ask spreads. We include lagged cross-correlations of spreads as explanatory variables, and lagged within-market autocorrelations as control variables in addition to the order flow variables of order imbalance, liquidity supply, liquidity demand and volume are included. In doing so, we look to determine the Granger causal variables to each asset's liquidity and determine the degree of cross-asset market liquidity that may exist.

$$
\begin{aligned}
\Delta \mathrm{S}_t^{\mathrm{spy}} &= \sum_{i=1}^{6} \alpha_{1,i} \Delta \mathrm{S}_{t-i}^{\mathrm{spy}} + \sum_{i=0}^{6} \alpha_{1,7+i} \Delta \mathrm{S}_{t-i}^{\mathrm{es}} + \sum_{i=0}^{6} \beta_{1,i} \Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \cdots + \sum_{i=0}^{6} \beta_{1,47+i} \Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t \\
\Delta \mathrm{S}_t^{\mathrm{es}} &= \sum_{i=1}^{6} \alpha_{2,i} \Delta \mathrm{S}_{t-i}^{\mathrm{spy}} + \sum_{i=1}^{6} \alpha_{2,7+i} \Delta \mathrm{S}_{t-i}^{\mathrm{es}} + \sum_{i=1}^{6} \beta_{2,i} \Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \cdots + \sum_{i=1}^{6} \beta_{2,47+i} \Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t \\
\Delta \mathrm{LS}_t^{\mathrm{spy}} &= \sum_{i=1}^{6} \alpha_{3,i} \Delta \mathrm{S}_{t-i}^{\mathrm{spy}} + \sum_{i=1}^{6} \alpha_{3,7+i} \Delta \mathrm{S}_{t-i}^{\mathrm{es}} + \sum_{i=1}^{6} \beta_{3,i} \Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \cdots + \sum_{i=0}^{6} \beta_{3,47+i} \Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t \\
\vdots \quad &= \qquad \vdots \\
\Delta \mathrm{Volume}_t^{\mathrm{es}} &= \sum_{i=1}^{6} \alpha_{10,i} \Delta \mathrm{S}_{t-i}^{\mathrm{spy}} + \sum_{i=1}^{6} \alpha_{10,7+i} \Delta \mathrm{S}_{t-i}^{\mathrm{es}} + \sum_{i=1}^{6} \beta_{10,i} \Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \cdots + \sum_{i=1}^{6} \beta_{10,47+i} \Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t
\end{aligned} \tag{9}
$$

[**Table 6: Cross-Asset Market Spread SVAR with Order Flow**]

In Table 6 we present the contemporaneous and first three lag coefficients of the SVAR in equation (9), which influence the ETF and futures spreads. The within-own market spread lags are statistically significant and generally negative in panels A and B. These results are similar to previous tables implying illiquidity risk is mitigated quickly in both the 1s and 10ms data samples. The future within-own market lagged order flow variables are generally significant expect for the order imbalance, whereas for the ETF, only the lagged liquid demand is significant. The cross-asset lag spread results are mixed, with little statistical significance, though the futures spread is generally significantly influenced by the ETF liquidity supply and demand order flow.

To get at the cross dependence of order flow, Table 7.A presents the impulse response of cross-asset market spreads to changes in order flow. In the futures market regressions, we find that changes in liquidity supply coefficients are statistically significant and negative. This means that both within-market futures orders and cross-market ETF orders that add liquidity to the limit order book tend to lower futures contract bid-ask spreads and improve liquidity at both 1s and 10ms frequencies. The within-market liquidity demand and volume coefficients for both panels are positive, indicating a decrease in liquidity in the market in response to liquidity-demanding trades that interact with existing liquidity supply in the order book. However, in the cross-asset market, the liquidity demand and volume coefficient for both periods are negative, implying that a given trade in one market does not imply an increase in illiqudity in the other market. Results for the

ETF market are similar but less significant, with the exception that cross-asset market volume in futures appears to increase the ETF's spread, and make them illiquid.

[**Table 7.A-B: Impulse Response of Cross-Asset Market Spreads**]

In Table 7.B we present a formulation closer to Brogaard et al. (2019) by adding variables that account for the relative NBBO location of order flow activities. In the case of illiquid securities, which have spreads wider than 1 tick, the predictions for the impact of order flow positioning are straightforward. Orders with limit prices inside the NBBO help narrow the spread; those at the NBBO leave the spread unchanged; and those outside the NBBO have the least impact. However, as we previously showed in Table 4.A, highly liquid index products that we analyze have 1 tick spread more than 97 percent of the time, when there is no room to place a liquidity supplying limit order inside the NBBO. The remaining 3 percent of the time represents volatile periods with rapidly changing prices. Thus, sells order at the NBBO, which might appear to be improving liquidity, in fact may truly represent falling prices. Because of these tradeoffs, we find weak and mixed impact of order flow pricing relative to NBBO on spreads.

4 Cross-Asset Market Price Discovery

Having demonstrated how cross-asset order flow can influence liquidity in Section 3, we now examine how it can influence price discovery. As price discovery should be influenced by both asset markets, understanding how order flow within and across markets contributes to the formation of prices collectively is critical to determining the potential for idiosyncratic asset events creating cross-asset spillovers in volatility.

We are interested not only how order flow dependence influences price discovery, through price returns but how it influences the co-integration of prices between the two assets (Harris et al. (1995)). In particular, can order flow help us understand how breakdowns in fundamental valuations occur (i.e. flash crashes) during market volatility? Additionally, as each asset's price is fundamentally interdependent, any deviations could create excess volatility as the two markets reconcile their evaluations. We look to answer this hypothesis by understanding whether an increase in activity in one market can create weakness in its price integration with the other market.

First, we analyze the directional impact of within and across market order flow on price returns within each market, separately for ETFs and futures. The dependent variables in the SVAR regressions, presented in equation (10), are the two assets' price returns. In addition to the lagged auto-correlation and lagged cross-correlation of returns as explanatory variables, the order flow variables of order imbalance, liquidity supply, liquidity demand, and volume are included.

Brogaard, Hendershott, and Riordan (2019) show that despite their lower individual price impact, limit orders provide the majority of price discovery because they are far more numerous than market orders. They show that more aggressive orders have a higher price impact. Market orders, the most aggressive order type, have the highest impact, followed by orders that change the national best bid and offer (NBBO), orders at the NBBO, and orders behind the NBBO. Our model below follows their structure by including liquidity demanding market orders and liquidity supplying limit orders at various levels of aggressiveness but our model has a significant extension because we include these terms not only for SPY own market but also from the ES cross-asset market and vice versa.

$$
\begin{aligned}
\Delta \mathrm{R}_t^{\mathrm{spy}} &= \sum_{i=1}^{6} \alpha_{1,i} \Delta \mathrm{R}_{t-i}^{\mathrm{spy}} + \sum_{i=0}^{6} \alpha_{1,7+i} \Delta \mathrm{R}_{t-i}^{\mathrm{es}} + \sum_{i=0}^{6} \beta_{1,i} \Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \cdots + \sum_{i=0}^{6} \beta_{1,47+i} \Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t \\
\Delta \mathrm{R}_t^{\mathrm{es}} &= \sum_{i=1}^{6} \alpha_{2,i} \Delta \mathrm{R}_{t-i}^{\mathrm{spy}} + \sum_{i=1}^{6} \alpha_{2,7+i} \Delta \mathrm{R}_{t-i}^{\mathrm{es}} + \sum_{i=1}^{6} \beta_{2,i} \Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \cdots + \sum_{i=1}^{6} \beta_{2,47+i} \Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t \\
\Delta \mathrm{LS}_t^{\mathrm{spy}} &= \sum_{i=1}^{6} \alpha_{3,i} \Delta \mathrm{R}_{t-i}^{\mathrm{spy}} + \sum_{i=1}^{6} \alpha_{3,7+i} \Delta \mathrm{R}_{t-i}^{\mathrm{es}} + \sum_{i=1}^{6} \beta_{3,i} \Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \cdots + \sum_{i=0}^{6} \beta_{3,47+i} \Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t \\
\vdots \quad &= \qquad \qquad \vdots \\
\Delta \mathrm{Volume}_t^{\mathrm{es}} &= \sum_{i=1}^{6} \alpha_{10,i} \Delta \mathrm{R}_{t-i}^{\mathrm{spy}} + \sum_{i=1}^{6} \alpha_{10,7+i} \Delta \mathrm{R}_{t-i}^{\mathrm{es}} + \sum_{i=1}^{6} \beta_{10,i} \Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \cdots + \sum_{i=1}^{6} \beta_{10,47+i} \Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t
\end{aligned}
\tag{10}
$$

Table 8 presents the impulse response of price returns to within- and cross-asset market order flow and volume based on equation (10). Order imbalance from both within and across markets most consistently relates to positive ETF and futures returns during benchmark as well as volatile periods at both 1s and 10 ms intervals. An increase in liquidity-demanding orders within and across markets negatively affects ETF and future returns in volatile periods indicating that such trades may be seller initiated.

[**Table 8: Impulse Response of Cross-Asset Market Price Returns**]

Table 9.A presents our final interconnectedness variable: the price correlation between the ETF and futures markets. In the top panel we divide the 1s intervals throughout the entire trading day into 11 groups based on the correlation between the ETF and futures asset price changes during that second. The groups range from very high correlation of +0.90 to +1 to opposite price movements in the last correlation group of 0 to -1. The groups are defined analogously in the bottom panel for 10ms intervals. When ETF and future asset volumes are high, prices co-move together strongly. The +0.90 to +1 correlation intervals have the highest trading volume and message traffic in both ETF and futures assets at both 1s and 10 ms frequencies.

[**Table 9.A-B: Impact of Order Flow on Price Correlation**]

In the ETF market, we generally find that lower spreads and proportionally lower quantities of liquidity supplying orders lead to higher levels of price correlations. Trades have different effects on price correlation depending on the frequency. For 1s aggregation, more trades result in higher price correlations. However, for 10ms aggregation, more trades are generally associated with lower correlations, although the relation is not monotonic. Order cancellations also have different effects on price correlation depending on the frequency. For 1s aggregation, more cancellations result in lower price correlations. However, for 10ms aggregation, the relation between cancellations and correlation is marginally U-shaped; high and low correlations are both associated with more cancellations.

In the futures market, for 1s aggregation, higher spreads and proportionally lower quantities of liquidity-supplying orders lead to greater of price correlation. But for 10ms aggregation, the association between price correlation and spread and new orders is non-monotonic. For 1s interval, more trades and fewer cancellations lead to higher price correlation, though the opposite is true at 10ms. At both frequencies, the relation between order imbalance and price correlation is non-monotonic. The correlations at the 1s interval are sometimes a nearly perfect 1.00, but at the 10ms interval the highest price correlation between the two markets is 0.80. Overall, we learn from Table 9.A that higher price correlations are associated with higher volume and message traffic.

Table 9.B presents changes in price correlation to supplement the above results on levels of correlations. For 1s interval, we see lower spreads lead to increased price correlations in both markets.

Higher volume and message traffic in both markets increase price correlations. Order imbalances do not significantly affect changes in price correlations. The impacts of volume, messages, and trades are opposite for 10ms regressions and are less monotonic.

The dependent variable in the SVAR equation (11) is correlation of ETF and futures high frequency returns. In addition to the lagged terms of returns correlation as explanatory variables, the order flow variables of order imbalance, liquidity supply, liquidity demand, and volume are included.

$$
\begin{aligned}
\rho_t^{\Delta \mathrm{R}} &= \sum_{i=1}^{6} \gamma_{1,i}\rho_{t-i}^{\Delta \mathrm{R}} + \sum_{i=0}^{6} \beta_{1,i}\Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \sum_{i=0}^{6} \beta_{1,7+i}\Delta \mathrm{LS}_{t-i}^{\mathrm{es}} + \cdots + \sum_{i=0}^{6} \beta_{1,47+i}\Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t \\
\Delta \mathrm{LS}_t^{\mathrm{spy}} &= \sum_{i=1}^{6} \gamma_{2,i}\rho_{t-i}^{\Delta \mathrm{R}} + \sum_{i=1}^{6} \beta_{2,i}\Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \sum_{i=0}^{6} \beta_{2,7+i}\Delta \mathrm{LS}_{t-i}^{\mathrm{es}} + \cdots + \sum_{i=0}^{6} \beta_{2,47+i}\Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t \\
\Delta \mathrm{LS}_t^{\mathrm{es}} &= \sum_{i=1}^{6} \gamma_{3,i}\rho_{t-i}^{\Delta \mathrm{R}} + \sum_{i=1}^{6} \beta_{3,i}\Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \sum_{i=1}^{6} \beta_{3,7+i}\Delta \mathrm{LS}_{t-i}^{\mathrm{es}} + \cdots + \sum_{i=1}^{6} \beta_{3,47+i}\Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t \\
\vdots \quad &= \qquad \vdots \\
\Delta \mathrm{Volume}_t^{\mathrm{es}} &= \sum_{i=1}^{6} \gamma_{9,i}\rho_{t-i}^{\Delta \mathrm{R}} + \sum_{i=1}^{6} \beta_{9,i}\Delta \mathrm{LS}_{t-i}^{\mathrm{spy}} + \sum_{i=1}^{6} \beta_{9,7+i}\Delta \mathrm{LS}_{t-i}^{\mathrm{es}} + \cdots + \sum_{i=1}^{6} \beta_{9,47+i}\Delta \mathrm{Volume}_{t-i}^{\mathrm{es}} + \epsilon_t
\end{aligned}
\tag{11}
$$

In Table 10 we present the impulse response of equation (11) with price correlation as the main dependent variable of interest. We find that the liquidity demand and volume coefficients are generally positive and statistically significant in various regression specifications, with 1s and 10ms frequencies in baseline and volatility periods. This means that higher trading volume is generally associated with higher correlation, although the impact of ETF trades is weaker at 10ms intervals. However, liquidity supply coefficients are negative, indicating that greater liquidity supply weakens the price integration between ETF and futures prices.

[**Table 10: Impulse Response of Price Return Correlation**]

5 Cross-Asset Fragility Case Studies

Given the observed interdependence of liquidity and pricing of our two assets, we next address the potential fragility this relationship may cause in the event of one market suffering an unexpected disruption. We examine this potential financial stability concern by using two independent exogenous shock that are unrelated directly to the fundamental price of either asset being traded. We use the October 30, 2014 NYSE SIP failure, a disruption to the ETF's NBBO system, and the May 6, 2010 Flash Crash, where a futures trader's algorithm caused a spurious sell off in E-mini futures. We choose these two events as they both cause disruptions in normal trading activities but do not lead to either asset market's closure.

Fundamentally, we are interested in answering two questions linked to financial stability. First, do such shocks cause changes in how cross-asset market order flow activities influence liquidity and price, particularly in the case of the non-shocked asset market? Second, do we observe any changes in order activity that are indicative of enhancing market resiliency or causing negative spill overs?

5.1 Securities Information Processor Failure: ETF to Futures

In equity markets, a listing exchange's securities information processor (SIP) collects, processes, and disseminates the information in a single, consolidated, and easily consumed data feed to determine NBBO quotations. Although other avenues exist for disseminating prices, there is only one official SIP for each major listing exchange. The failure of the SIP results in a marketwide trading halt that can impair price discovery and liquidity provision, as when of Nasdaq halted trading for three hours in August 2013. Additionally such an event might lead to spillovers to the futures market.

We specify look at a 27 minute disruption at the NYSE SIP, where SPY is listed, on October 30, 2014. At approximately 1:07 p.m., there was a network hardware failure impacting the data feeds at the primary data center. This event lead to the SIP not sending NBBO price information. However it did not lead to a trading halt. At approximately 1:34 p.m., NYSE switched over to the secondary data center in Chicago, allowing normal pricing to resume. This meant that exchanges, dark pools, and brokerage internalizers that relied on the SIP for NBBO quotes were potentially trading at different prices during this period, though any exchange with a direct feeds could still price off of accurate information.

Therefore, for at least 27 minutes, there was a degree of price uncertainty that may have influenced where price discovery occurred and how liquid the ETF and futures were. Participants who had subscriptions to private data feeds from exchanges were able to obtain some information that further enhanced the information asymmetry among market participants.

[**Table 11.A: The October 30 2014 NYSE SIP Disruption**]

In Table 11.A, we observe the SIP outage resulted in reduced message traffic and reduced liquidity supply activity in both the ETF and futures market, indicative of reduced liquidity supply. Due to the lack of quotation information in the SIP public feed, price volatility increased during the outage period. Increased volatility appears to have led to increased ETF trading volumes through increased liquidity demand and aggressive trading, despite the lack of pricing information.

[**Table 11.B: SIP Disruption: Impulse Response of Cross-Asset Market Price Spreads**]

To more formally analyze this event, we implement our three order flow SVARs. The impulse response of spreads to within- and cross-asset market activity during the SIP outage is presented in Table 11.B. Recall from Table 7.A that in the benchmark periods increased liquidity supply activity reduces spreads, whereas increased liquidity demand increases spreads and that these relations are weaker in volatile periods. This suggests that the SIP outage results in a similarly weakening of the cross-asset market relationship, in contrast to the benchmark pre and post periods where were see ETF and futures liquidity supply influencing spreads.

[**Table 11.C: SIP Disruption: Impulse Response of Cross-Asset Market Price Returns**]

Table 11.C presents the impulse response of price returns to within- and cross-asset order activity. Previously, we showed that order imbalances from both within and across markets most consistently relates to positive ETF and futures returns during the benchmark and volatile periods. This result appears to hold even during the SIP outage, and suggest that the price returns relationship is rooted deeply in economic fundamentals. Additionally, we find that thought volatility was generally low during the event nearly all the cross-asset activities were significant during the outage period. However, prior and post the event they were insignificant. The increased cross-asset activity highlights how cross-asset trading can provide a robustness mechanism to market by allowing the price information of one market to keep the other informed and prices stable.

[Table 11.D: SIP Disruption: Impulse Response of Price Return Correlation]

Finally in Table 11.D we present the impulse response of price return correlation to Futures and ETF order flow activity. We find that the Futures contract liquidity demand and volume coefficients are generally positive and statistically significant in all periods. In contrast, SPY demand, which generally increases liquidity demand, is not significant during the SIP outage period and immediately thereafter. Thus, futures trading has a stronger impact on correlations than ETF trades. Importantly, liquidity supply coefficients are negative for both Futures and ETFs, indicating that greater liquidity supply weakens the price integration between ETF and futures prices even during the SIP outage period.

5.2 The May 6, 2010 Flash Crash: Futures to ETF

On May 6, 2010, U.S. financial markets experienced a systemic intra-day event - the Flash Crash - where a large automated selling program was rapidly executed in the ES futures market. At 2:32 p.m., against the backdrop of unusually high volatility and thinning liquidity, a large mutual fund complex initiated an automated program to sell a total of 75,000 ES contracts as a hedge to an existing equity position (Securities and Exchange Commission and Commodity Futures Trading Commission (2010)). However, on May 6, when markets were already under stress, this automated program, which would normally execute over several hours, executed the majority of its position over just 23 minutes.

In Table 12.A, we separate the event into two parts. The first part includes the flash crash, during which the large automated selling program ran before being shut off by the market circuit breaker. The second part includes the flash rally, which started once the market circuit breaker was released, leading to a reversal of most of the ES price declines caused by the large automated selling program.

[Table 12.A: The May 6 2010 Flash Crash]

From Table 12.A, we can see the two flash crash periods have widening of spreads, increased volumes and increased volatility. Differences of note between the two periods, beyond the direction of price returns, are the amount of message traffic during the crash, and the significantly wider spreads and higher proportion of trades, especially in the futures contract at the beginning of the crash. Additionally, we can see that during the crash as the automated selling programs was executed in the futures market, its order imbalance reflected the selling pressure (less than 0.50). Where as in the ETF market we see buying pressures reflected in its order imbalance (greater than 0.50), suggestive of arbitrage forces trying to keep prices co-integrated. During the flash rally, we can see a reversal in order imbalance.

[**Table 12.B: Flash Crash: Impulse Response of Cross-Asset Market Price Spreads**]

In examining the impulse response of spreads, in Table 12.B, we find that cross-asset order flow activity wasn't making its usual contribution to liquidity, as measured by spreads, during the flash crash. However, during the flash rally, when spreads widened, we see that within-own market activity does significantly explain liquidity. This result suggests that the market liquidity in ETF and futures appeared to act independent of each other during the recovery.

[**Table 12.C: Flash Crash: Impulse Response of Cross-Asset Market Price Returns**]

In Table 12.C we present the impulse response of price returns and find that the cross-asset price return relationship seems to hold steady through the flash crash period. However, during the price rally, we find that the two markets appear to lose their interdependence and the prices of the two assets move independently. This event, suggests how poor execution in one market can lead to cross-asset spillovers effects and increased price fragility.

[**Table 12.D: Flash Crash: Impulse Response of Price Return Correlation**]

Finally, in Table 12.D we present the impulse response of price return correlation. Except for the future's trading volume, all other coefficients on regressions model are statistically insignificant during the flash crash period. Thus, the usual lock-step relation between Futures and ETFs seems to break down during the flash crash, showing signs of market fragility. But the relations were restored at 3 p.m. after the flash rally recovery was over.

6 Conclusion

Cross-asset and multi-market analysis of interconnected assets has been of significant interest to academics and regulators, as this work helps to explain the processes and dynamic of price discovery. More importantly, it helps identify potential illiquidity issues that can emerge during periods of volatility, as the Brady Commission Report did for 1987's Black Monday. As financial markets have grown more automated and market participants' trading capacity and access to substitute assets have expanded, volatility events such as May 6, 2010 and August 24, 2015, have raised concerns about the stability of capital markets, and highlighted the need to assess the complex linkages among markets, factors that could cause 'flash events' to propagate across markets.

In this paper we examine intra-day message activity across two tightly related markets, the S&P 500 E-mini futures contract, and S&P 500 exchange-traded fund, SPY. By employing order flow data we can examine several dimensions of the co-movement between these two assets. First, we examine the consequences of cross-asset market order flow on each asset's liquidity, measured by bid-ask spreads. We show spreads decline when the proportion of liquidity-supplying orders increases and that of liquidity-demanding orders decreases for both ETF and futures.

Second, we examine the impact of cross-asset market order flow and find it to be a key component of price discovery, with several features of one asset's order flow significantly influencing the other's price during periods of market volatility. Generally, buy (sell) order flow imbalance from both markets most consistently relate to positive (negative) ETF and futures returns. Additionally, we test the impact of order flow on price correlation. Higher cross-asset price correlation is associated with higher volume, liquidity demand, and message traffic in both ETF and futures. Increased liquidity supply within market or across markets reduces price correlation. However, this general pattern is disturbed in periods with volatility.

Finally, we examine two cases studies and find that cross-asset activity has mixed effects on price discovery stability. In the case of the October 30, 2014 New York Stock Exchange Securities Information Processor failure, we find that increased cross-asset activity provided a robustness mechanism to the markets by allowing the price information of one market to keep the other informed and stable. However, in the case of the May 6, 2010 Flash Crash, we find how poor execution in one market can lead to cross-asset spillovers effects and increased price fragility across the two assets.

Overall, this paper seeks to determine whether cross-asset market order flow influences liquidity and price discovery in a systemically important manner. After controlling for order flow variables together, we find that an increase in activity in one market can weaken price integration with the other market in volatile periods. As each asset's price is interdependent, any deviations can create excess volatility as the two markets reconcile their valuations. Overall, we find that cross-asset market spillover effects are generally short lived, lasting no longer than a second.

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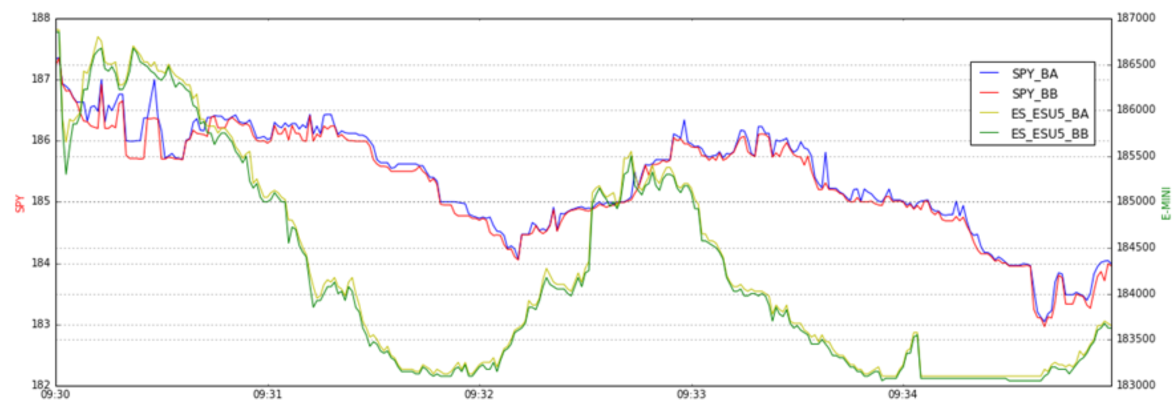
Figures and Tables

Figure 1: Bid-Ask Spreads of S&P500 ETF and Futures Contract: Normal and Volatile

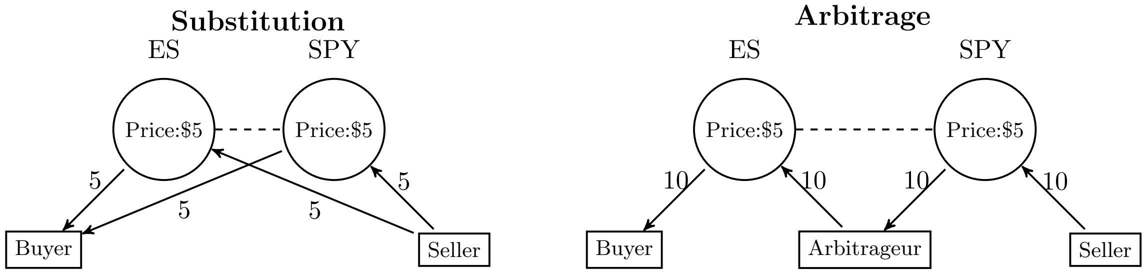
(a) Normal Market Open: August 22 2016



(b) Volatile Market Open: August 24 2015

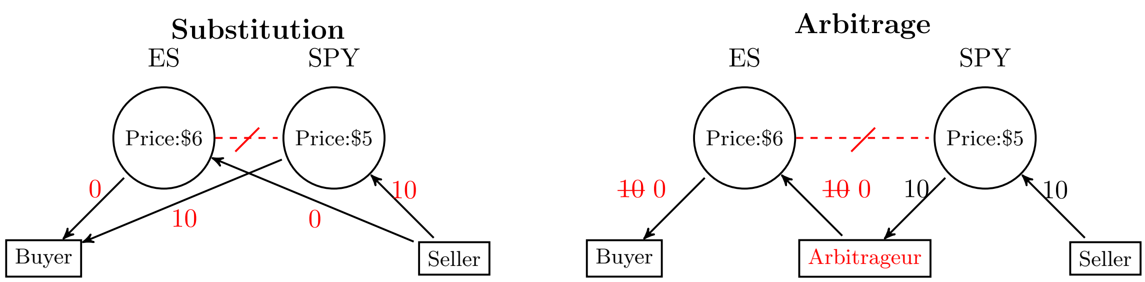
Note: Panels A and B plot the intraday prices for the SPDR SP 500 ETF (ticker symbol SPY) and E-mini SP 500 futures (ticker symbol ES) at each market's open. Each plot shows the best bid (SPY: red, ES: yellow) and best ask (SPY: blue, ES: green) price for the two securities between 9:30AM and 9:35AM EST. Panel A shows a typical market open, where bid-ask spreads are one tick, and the two assets prices are in near lock step. Panel B shows a high-volatility day, where bid-ask spreads widen and contract, and the two asset's prices move partially independent of one another.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Figure 2: Example of Cross-Asset Market Trading



Note: The example figures represent how two forms of trading activity, substitution and arbitrage, enable the two assets' prices, ES and SPY, to stay interconnected (depicted by the dashed line). The two circle nodes represent the two asset markets, through which buyers and sellers trade and form price. The arrows depict the flow of shares/contracts bring moved from one group's inventory through the market to anothers. In the case of substitution, buyers and sellers equally distribute 10 shares/contracts across the two markets, 5 to ES and 5 to SPY. In the case of arbitrage, if buyers and sellers choose to concentrate their flow of 10 shares/contracts to different markets, buyers in ES and sellers in SPY, then the arbitrageur can redistribute the concentrated buying and selling demand and capture the potential difference in price that might arise.
Source: Authors' creation.

Figure 3: Example of Cross-Asset Market Trading and Price Dislocation



Note: The example figures represent how the two forms of trading activity, substitution and arbitrage, can individually fail to keep the two assets' prices, ES and SPY, interconnected (depicted by the dashed line, with a slash). The two circle nodes represent the two asset markets, through which buyers and sellers trade and form price. The arrows depict the flow of shares/contracts bring moved from one group's inventory through the market to anothers. In the case of substitution, if buyers and sellers choose to concentrate their 10 shares/contracts to a single market, SPY, then out of a lack of activity ES's price becomes stale and disconnected from SPY. In the case of arbitrage, if buyers and sellers choose to concentrate their 10 shares/contracts to different markets, buyers in ES and sellers in SPY, and the arbitrageur cannot redistribute the concentrated buying and selling demand between the markets, prices can become stale.
Source: Authors' creation.

Table 1: Intraday Transaction Statistics

Panel A: Baseline Days										
S&P 500 ETF										
	Volume	Message Traffic	Trades	New Order	Cancel	Other	Order Imbalance	Spreads	Returns (10ms)	Returns (1s)
Mean	37.361	7.945	0.010	0.510	0.457	0.022	0.502	1.005	6.859E-6	4.991E-3
Std. Dev.	684.296	43.121	0.066	0.301	0.298	0.116	0.407	0.153	5.786E-1	5.123
Min	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	-45.20	-78.75
Median	0.000	0.000	0.000	0.500	0.500	0.000	0.500	1.000	0.000	0.000
Max	215,008.000	4809	1.000	1.000	1.000	1.000	1.000	7.000	49.97	65.18
S&P 500 Futures										
	Volume	Message Traffic	Trades	New Order	Cancel	Other	Order Imbalance	Spread	Returns (10ms)	Returns (1s)
Mean	0.588	1.586	0.036	0.519	0.372	0.072	0.499	1.003	7.297E-6	4.695E-4
Std. Dev.	10.548	10.677	0.110	0.379	0.368	0.202	0.451	0.056	1.237	7.765
Min	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	-74.100	-86.310
Median	0.000	0.000	0.000	0.500	0.333	0.000	0.500	1.000	0.000	0.000
Max	2,562.000	714.000	1.000	1.000	1.000	1.000	1.000	6.000	61.660	62.780
Panel B: Volatile Days										
S&P 500 ETF										
	Volume	Message Traffic	Trades	New Order	Cancel	Other	Order Imbalance	Spread	Returns (10ms)	Returns (1s)
Mean	78.830	11.397	0.021	0.533	0.406	0.041	0.487	1.005	-1.200E-4	-1.101E-2
Std. Dev.	930.965	45.896	0.092	0.292	0.283	0.147	0.389	0.769	1.627	10.660
Min	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	-547.000	-472.600
Median	0.000	1.000	0.000	0.500	0.444	0.000	0.500	1.000	0.000	0.000
Max	260,069.000	8850	1.000	1.000	1.000	1.000	1.000	105.000	547.000	385.900
S&P 500 Futures										
	Volume	Message Traffic	Trades	New Order	Cancel	Other	Order Imbalance	Spread	Returns (10ms)	Returns (1s)
Mean	0.972	2.736	0.036	0.517	0.365	0.082	0.504	1.030	-1.350E-4	-1.256E-2
Std. Dev.	11.660	11.562	0.104	0.364	0.350	0.207	0.444	0.188	2.092	12.010
Min	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	-363.600	-643.800
Median	0.000	0.000	0.000	0.500	0.333	0.000	0.500	1.000	0.000	0.000
Max	2,635.000	742.000	1.000	1.000	1.000	1.000	1.000	24.000	311.400	348.400

Note: Sample of 553.73 million messages in 23.4 million 10 millisecond periods in 10 days ETF and Futures market between January 2014 and August 2017 is drawn from the 5 highest expected volatility days and the 5 highest unexpected volatility days in Panel 2, along with 10 matched neutral volatility benchmark days in Panel 1. All variables are averaged or aggregated for every 10 millisecond bucket between the trading hours of 9:30AM and 4PM. Each panel is based on 23.4 million buckets. Trades, new limit orders, cancels and other messages are expressed as the proportion of total message traffic. Price returns are presented in basis points and spreads are presented in tick units. Volume is measured in number of ETF shares/E-mini contracts.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Appendix

Table 2: Cross-Asset Market Time-Series Correlations

	Δ Order Imbalance		Δ Liquidity Supply		Δ Liquidity Demand		ΔLiquidity Withdrawal	
Panel A: 1 Second Aggregations								
	Baseline	Volatile	Baseline	Volatile	Baseline	Volatile	Baseline	Volatile
-6	-0.001	0.002	0.001	-0.003	-0.001	0.002	-0.002	0.000
-5	0.000	-0.008	0.000	-0.002	0.002	0.000	0.000	-0.002
-4	0.004	0.011	0.002	0.005	-0.003	-0.001	0.001	-0.001
-3	-0.005	-0.004	-0.004	-0.002	0.003	0.000	-0.004	0.003
-2	0.001	-0.009	0.009	0.008	0.005	0.004	0.000	-0.013
-1	-0.191	-0.317	-0.050	-0.108	-0.014	-0.017	0.006	0.031
0	0.332	0.599	0.086	0.198	-0.007	0.008	-0.001	-0.032
1	-0.113	-0.238	-0.043	-0.103	0.020	0.015	0.001	0.022
2	-0.020	-0.025	-0.001	0.002	-0.005	-0.006	-0.002	-0.009
3	-0.002	-0.012	0.001	0.002	0.002	-0.002	-0.002	0.001
4	-0.001	0.011	0.002	-0.001	-0.001	0.001	0.005	0.004
5	-0.004	-0.008	-0.003	0.004	-0.001	-0.001	-0.007	-0.006
6	0.000	0.001	0.006	-0.002	0.000	-0.002	0.009	0.002
Panel B: 10 Millisecond Aggregations								
	Δ Order Imbalance		Δ Liquidity Supply		Δ Liquidity Demand		ΔLiquidity Withdrawal	
	Baseline	Volatile	Baseline	Volatile	Baseline	Volatile	Baseline	Volatile
-6	0.005	0.000	0.008	0.004	0.002	0.002	-0.009	-0.001
-5	-0.013	-0.010	-0.022	-0.007	-0.007	-0.005	0.020	0.004
-4	-0.003	0.001	0.006	-0.002	0.004	0.000	-0.005	0.000
-3	0.002	-0.006	0.003	-0.002	0.002	0.002	-0.007	-0.002
-2	-0.013	-0.017	-0.001	-0.017	-0.002	0.002	0.007	0.010
-1	-0.049	-0.026	-0.013	0.017	-0.007	-0.006	-0.002	-0.009
0	0.104	0.087	0.036	0.042	0.002	-0.003	-0.001	-0.025
1	0.015	0.041	-0.006	-0.020	0.017	0.012	0.000	0.020
2	0.003	-0.009	-0.004	-0.005	-0.003	0.002	0.005	0.011
3	-0.014	-0.023	-0.001	-0.006	-0.006	-0.004	-0.002	-0.008
4	0.001	-0.001	-0.003	0.000	0.001	0.001	-0.003	0.000
5	-0.002	-0.003	-0.001	0.001	0.000	0.001	0.001	0.001
6	-0.007	-0.003	0.000	0.000	0.002	0.000	0.000	0.000

Note: Row 0 in the first column of each Panel shows the contemporaneous correlations between SPY ETF and E-mini Futures. In rows with any negative number i in the first column, the ith lagged values of futures contract is matched with the current time bucket of SPY ETF. In rows with positive numbers, lead values of futures are matched with the current time bucket of SPY ETF. Change (Δ) for each order flow variable is defined as its value in the current interval minus its value in the previous interval.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 3: Cross-Asset Market Order Flow SVAR

	Panel A: 1 Second				**Panel B: 10 Millisecond**			
	Baseline		Volatile		Baseline		Volatile	
	ETF	Future	ETF	Future	ETF	Future	ETF	Future
Within Market	**Order Imbalance SVAR**							
ΔOL_1	-0.828^{***}	-0.698^{***}	-0.838^{***}	-0.682^{***}	-0.284^{***}	-0.211^{***}	-0.321^{***}	-0.247^{***}
ΔOL_2	-0.703^{***}	-0.545^{***}	-0.723^{***}	-0.537^{***}	-0.093^{***}	-0.048^{***}	-0.116^{***}	-0.071^{***}
ΔOL_3	-0.602^{***}	-0.438^{***}	-0.628^{***}	-0.439^{***}	-0.035^{***}	-0.014^{***}	-0.047^{***}	-0.024^{***}
Cross Market								
ΔOI_0	0.195^{***}	-	0.325^{***}	-	0.058^{***}	-	0.056^{***}	-
ΔOL_1	-0.018^{***}	0.026^{***}	-0.017^{***}	0.056^{***}	-0.009^{***}	0.008^{***}	0.002^{***}	0.019^{***}
ΔOL_2	-0.024^{***}	0.010^{**}	-0.025^{***}	0.100^{***}	-0.010^{***}	0.004^{***}	-0.007^{***}	0.006^{***}
ΔOL_3	-0.027^{***}	0.001^{***}	-0.026^{***}	0.118^{***}	-0.004^{***}	-0.001^{***}	-0.007^{***}	-0.004^{***}
Within Market	**Liquidity Supply SVAR**							
ΔLS_{-1}	-0.990^{***}	-0.838^{***}	-0.999^{***}	-0.825^{***}	-0.320^{***}	-0.237^{***}	-0.366^{***}	-0.296^{***}
ΔLS_{-2}	-0.895^{***}	-0.700^{***}	-0.912^{***}	-0.660^{***}	-0.102^{***}	-0.060^{***}	-0.138^{***}	-0.090^{***}
ΔLS_{-3}	-0.790^{***}	-0.587^{***}	-0.809^{***}	-0.522^{***}	-0.034^{***}	-0.015^{***}	-0.053^{***}	-0.029^{***}
Cross Market								
ΔLS_0	0.025^{***}	-	0.059^{***}	-	0.015^{***}	-	0.022^{***}	-
ΔLS_{-1}	0.000	-0.035^{***}	0.000	-0.088^{***}	-0.001^{***}	0.000^{**}	0.013^{***}	-0.004^{***}
ΔLS_{-2}	0.002^{**}	-0.063^{***}	-0.001	-0.141^{***}	-0.001^{***}	-0.001^{***}	0.000	-0.005^{***}
ΔLS_{-3}	0.002^{*}	-0.073^{***}	-0.001	-0.160^{***}	0.001^{***}	-0.001^{***}	-0.003^{***}	-0.005^{***}
Within Market	**Liquidity Demand SVAR**							
ΔLD_{-1}	-0.840^{***}	-0.865^{***}	-0.814^{***}	-0.865^{***}	-0.316^{***}	-0.260^{***}	-0.371^{***}	-0.309^{***}
ΔLD_{-2}	-0.731^{***}	-0.743^{***}	-0.696^{***}	-0.736^{***}	-0.106^{***}	-0.079^{***}	-0.150^{***}	-0.102^{***}
ΔLD_{-3}	-0.638^{***}	-0.636^{***}	-0.608^{***}	-0.619^{***}	-0.037^{***}	-0.026^{***}	-0.063^{***}	-0.035^{***}
Cross Market								
ΔLD_0	-0.003^{***}	-	0.011^{***}	-	0.001^{***}	-	-0.01^{**}	-
ΔLD_{-1}	-0.007^{***}	0.066^{***}	-0.002^{***}	0.064^{***}	-0.002^{***}	0.007^{***}	-0.004^{***}	0.005^{***}
ΔLD_{-2}	-0.008^{***}	0.084^{***}	0.000	0.082^{***}	-0.002^{***}	0.002^{***}	-0.002^{***}	0.004^{***}
ΔLD_{-3}	-0.009^{***}	0.101^{***}	0.002	0.085^{***}	-0.001^{***}	-0.001^{***}	-0.000	0.001^{***}
Within Market	**Liquidity Withdrawal SVAR**							
ΔLW_{-1}	-0.960^{***}	-0.839^{***}	-0.920^{***}	-0.865^{***}	0.045^{***}	-0.001^{***}	-0.369^{***}	-0.299^{***}
ΔLW_{-2}	-0.855^{***}	-0.701^{***}	-0.813^{***}	-0.736^{***}	0.039^{***}	0.002^{***}	-0.140^{***}	-0.094^{***}
ΔLW_{-3}	-0.750^{***}	-0.582^{***}	-0.713^{***}	-0.619^{***}	0.040^{***}	-0.002^{***}	-0.052^{***}	-0.032^{***}
Cross Market								
ΔLW_0	0.002^{***}	-	-0.004^{***}	-	-	-	0.011^{***}	-
ΔLW_{-1}	0.004^{***}	0.006	0.009^{***}	0.064^{***}	-0.811^{***}	-0.322^{***}	-0.008^{***}	0.006^{***}
ΔLW_{-2}	0.006^{***}	0.001	0.009^{***}	0.082^{***}	-0.651^{***}	-0.103^{***}	-0.000	0.007^{***}
ΔLW_{-3}	0.005^{***}	-0.004	0.009^{***}	0.085^{***}	-0.526^{***}	-0.033^{***}	0.000	0.001^{***}

Note: Panels A and B represent the regression coefficients for volatile and benchmark periods in ETF and Futures market. Dependent variable is the change in the order flows variables in the current period and explanatory variables are 6 lags each of the change in order imbalance within the market and in cross market respectively. The ETF regression also includes the contemporaneous futures order flow variable as an explanatory variable. Column 1 on the left represents the lagged order imbalance activity for 3 seconds whereas the 10 millisecond regressions on the right include 30 milliseconds. The asterisks ***,**, and *, indicates that coefficients are statistically significant at the 1, 5 and 10 percent levels, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 4.A: Within Market Spread and Order Flow

		S&P 500 ETF											
Within Market		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1 Second													
1 Tick	97.84	5,799	962	0.492	0.022	0.486	0.495	5,806	963	0.492	0.022	0.486	0.495
		(15,630)	(1,055)	(0.036)	(0.025)	(0.039)	(0.127)	(14,937)	(1,054)	(0.036)	(0.025)	(0.039)	(0.127)
2+ Ticks	2.16	9,037	1,100	0.486	0.036	0.478	0.501	8,700	1,054	0.491	0.032	0.477	0.500
		(16,718)	(1,063)	(0.028)	(0.042)	(0.042)	(0.106)	(35,223)	(1,095)	(0.03)	(0.043)	(0.043)	(0.113)
Difference		3, 238	138	−0.006	0.014	−0.008	0.006	2, 894	90	−0.002	0.01	−0.008	0.004
10 Millisecond													
1 Tick	97.62	95	16	0.525	0.016	0.459	0.493	96	16	0.525	0.016	0.459	0.493
		(1,255)	(56)	(0.296)	(0.082)	(0.296)	(0.397)	(1,269)	(0,056)	(0.296)	(0.082)	(0.296)	(0.397)
2+ Ticks	2.38	182	16	0.531	0.034	0.435	0.501	134	16	0.541	0.029	0.430	0.502
		(2,809)	(62)	(0.282)	(0.122)	(0.28)	(0.384)	(2,527)	(0,057)	(0.279)	(0.117)	(0.277)	(0.389)
Difference		087	0	0.006	0.018	−0.024	0.008	038	0	0.017	0.013	−0.029	0.009
		S&P 500 Future											
1 Second													
1 Tick	98.52	78	216	0.510	0.081	0.409	0.501	78	217	0.509	0.082	0.409	0.501
		(172)	(265)	(0.096)	(0.085)	(0.097)	(0.211)	(174)	(266)	(0.097)	(0.086)	(0.097)	(0.211)
2+ Ticks	1.48	114	281	0.455	0.130	0.415	0.498	75	237	0.516	0.091	0.393	0.497
		(229)	(334)	(0.116)	(0.135)	(0.134)	(0.229)	(159)	(296)	(0.122)	(0.126)	(0.121)	(0.258)
Difference		37	65	−0.055	0.049	0.007	−0.002	−3	20	0.007	0.01	−0.016	−0.003
10 Millisecond													
1 Tick	98.43	2	5	0.549	0.062	0.389	0.502	2	5	0.548	0.063	0.389	0.502
		(17)	(17)	(0.362)	(0.198)	(0.354)	(0.445)	(17)	(17)	(0.362)	(0.199)	(0.354)	(0.445)
2+ Ticks	1.57	4	9	0.490	0.123	0.386	0.512	2	8	0.556	0.070	0.373	0.508
		(28)	(22)	(0.347)	(0.243)	(0.34)	(0.414)	(17)	(20)	(0.339)	(0.202)	(0.328)	(0.429)
Difference		3	4	−0.058	0.061	−0.002	0.01	0	3	0.009	0.007	−0.016	0.007

Note: The sample is divided into two groups based on size of bid-ask spreads measured in the number of ticks as shown in the first column, at the end of the current interval. Two separate panels are presented for the SPY ETF and ES futures market, respectively, for within market order flow at 1 second or 10 milliseconds before (columns on the left) and after (columns on the right) the given spread is observed. Columns New Order, Trade, Cancel, OI map the liquidity supply, liquidity demand, liquidity withdrawal, and order imbalance variables, respectively, during the current interval (pre-activity) and next interval (post-activity). The difference row is the average value of the variable in 2+ tick intervals minus the average value of the variable 1 tick intervals.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 4.B: Cross-Asset Market Spread and Order Flow

		S&P 500 ETF											
Cross-Asset		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1 Second													
1 Tick	98.52	5,770	956	0.492	0.022	0.486	0.495	5,773	957	0.492	0.022	0.486	0.495
		(15,541)	(1,050)	(0.035)	(0.025)	(0.039)	(0.126)	(15,245)	(1,052)	(0.035)	(0.025)	(0.039)	(0.126)
2+ Ticks	1.48	10,672	1,294	0.484	0.034	0.482	0.504	10,395	1,176	0.491	0.035	0.474	0.500
		(20,216)	(1,283)	(0.026)	(0.043)	(0.043)	(0.115)	(31,742)	(1,220)	(0.027)	(0.044)	(0.042)	(0.13)
Difference		4, 902	338	−0.008	0.012	−0.004	0.008	4, 622	218	−0.001	0.013	−0.011	0.005
10 Millisecond													
1 Tick	98.43	109	19	0.512	0.016	0.472	0.492	110	19	0.512	0.016	0.472	0.492
		(1,345)	(64)	(0.271)	(0.075)	(0.272)	(0.373)	(1,345)	(0,065)	(0.271)	(0.075)	(0.272)	(0.373)
2+ Ticks	1.57	217	32	0.525	0.033	0.442	0.502	191	28	0.539	0.033	0.428	0.501
		(1,826)	(81)	(0.241)	(0.114)	(0.24)	(0.343)	(1,789)	(0,068)	(0.237)	(0.113)	(0.236)	(0.352)
Difference		108	13	0.013	0.017	−0.03	0.01	082	9	0.027	0.017	−0.044	0.009
		S&P 500 Future											
1 Second													
1 Tick	97.84	77	213	0.510	0.081	0.409	0.500	77	213	0.510	0.081	0.409	0.501
		(173)	(265)	(0.098)	(0.086)	(0.098)	(0.213)	(172)	(264)	(0.098)	(0.086)	(0.098)	(0.212)
2+ Ticks	2.16	114	294	0.486	0.122	0.392	0.502	115	292	0.487	0.123	0.391	0.497
		(192)	(305)	(0.081)	(0.119)	(0.086)	(0.169)	(210)	(318)	(0.083)	(0.118)	(0.086)	(0.178)
Difference		37	81	−0.024	0.04	−0.017	0.001	38	78	−0.023	0.041	−0.019	−0.004
10 Millisecond													
1 Tick	97.62	1	3	0.536	0.070	0.394	0.503	1	3	0.536	0.070	0.394	0.503
		(14)	(14)	(0.352)	(0.207)	(0.344)	(0.439)	(14)	(14)	(0.352)	(0.207)	(0.344)	(0.439)
2+ Ticks	2.38	2	4	0.522	0.110	0.368	0.515	2	4	0.521	0.107	0.371	0.511
		(22)	(16)	(0.351)	(0.253)	(0.336)	(0.434)	(18)	(17)	(0.35)	(0.252)	(0.335)	(0.433)
Difference		1	1	−0.014	0.039	−0.025	0.012	0	1	−0.014	0.037	−0.022	0.008

Note: The sample is divided into two groups based on size of bid-ask spreads measured in the number of ticks as shown in the first column, at the end of the current interval. Two separate panels are presented for the SPY ETF and ES futures market, respectively, for within market order flow at 1 second or 10 milliseconds before (columns on the left) and after (columns on the right) the given spread is observed. Columns New Order, Trade, Cancel, OI map the liquidity supply, liquidity demand, liquidity withdrawal, and order imbalance variables, respectively, during the current interval (pre-activity) and next interval (post-activity). The difference row is the average value of the variable in 2+ tick intervals minus the average value of the variable 1 tick intervals.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 5.A: Impact of Order Flow on Within Market Spread Change

Δ Within		S&P 500 ETF						S&P 500 Future					
Market Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1 Second													
-6≥	0.04	21,330	724	0.470	0.140	0.389	0.502	282	153	0.291	0.584	0.126	0.494
-5	0.01	15,914	714	0.478	0.105	0.418	0.491	375	256	0.319	0.476	0.206	0.635
-4	0.01	18,060	1,060	0.478	0.105	0.417	0.524	217	97	0.317	0.449	0.234	0.396
-3	0.02	25,367	1,151	0.478	0.111	0.410	0.530	251	142	0.345	0.460	0.195	0.434
-2	0.06	19,553	1,303	0.493	0.063	0.445	0.505	263	272	0.392	0.349	0.259	0.420
-1	2.67	9,608	1,226	0.501	0.028	0.471	0.496	77	208	0.493	0.093	0.414	0.507
0	94.38	5,555	930	0.502	0.022	0.476	0.495	77	194	0.513	0.083	0.403	0.501
1	2.67	9,017	1,192	0.503	0.026	0.471	0.497	129	224	0.523	0.085	0.392	0.498
2	0.06	18,402	1,226	0.500	0.052	0.448	0.515	366	439	0.382	0.335	0.283	0.440
3	0.02	23,367	1,009	0.485	0.100	0.416	0.510	766	166	0.329	0.467	0.203	0.469
4	0.01	26,919	792	0.486	0.091	0.424	0.533	429	306	0.324	0.484	0.192	0.368
5	0.01	23,872	939	0.483	0.097	0.419	0.484	464	91	0.273	0.574	0.152	0.486
6≤	0.04	28,491	736	0.477	0.123	0.400	0.507	528	165	0.273	0.575	0.152	0.618
10 Millisecond													
-6≥	0.00	2,520.2	44.3	0.476	0.127	0.397	0.505	23.7	17.2	0.256	0.511	0.232	0.491
-5	0.00	6,258.2	103.4	0.504	0.094	0.402	0.522	33.3	31.4	0.407	0.357	0.237	0.553
-4	0.00	8,906.1	182.0	0.481	0.100	0.419	0.514	20.3	21.2	0.307	0.540	0.154	0.389
-3	0.00	7,490.6	180.1	0.499	0.077	0.424	0.500	19.9	19.4	0.344	0.447	0.209	0.465
-2	0.01	4,018.4	141.8	0.501	0.052	0.447	0.498	26.7	23.8	0.433	0.304	0.263	0.476
-1	0.39	1,338.2	74.3	0.506	0.028	0.466	0.496	5.5	9.8	0.542	0.064	0.394	0.509
0	99.17	47.8	9.0	0.541	0.017	0.443	0.493	0.7	1.9	0.548	0.067	0.385	0.502
1	0.40	934.0	51.8	0.522	0.026	0.452	0.496	17.3	14.6	0.566	0.046	0.389	0.507
2	0.01	2,731.7	101.1	0.520	0.053	0.427	0.506	92.1	37.9	0.496	0.257	0.247	0.483
3	0.00	3,199.8	104.7	0.505	0.079	0.415	0.504	113.5	39.3	0.406	0.388	0.206	0.468
4	0.00	3,726.8	106.9	0.501	0.095	0.404	0.507	85.0	21.2	0.459	0.319	0.221	0.397
5	0.00	3,387.0	66.7	0.483	0.122	0.395	0.494	178.2	34.9	0.389	0.352	0.258	0.833
6≤	0.00	2,792.4	33.4	0.483	0.131	0.386	0.491	117.7	20.3	0.398	0.328	0.275	0.497

Note: The sample is divided into 13 groups based on change (end of current interval value minus end of previous interval value) in the within-market bid-ask spreads measured in the number of ticks as shown in the first column. The top panel presents the activity for 1 second interval and the bottom panel for 10 milliseconds interval preceding the spread change. Analysis for SPY ETF is on the left and that for ES Futures is on the right. Columns New Order, Trade, Cancel, OI map the liquidity supply, liquidity demand, liquidity withdrawal, and order imbalance variables, respectively, during the current interval.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 5.B: Impact of Order Flow on Cross-Asset Market Spread Change

Δ Cross		S&P 500 ETF						S&P 500 Future					
Market Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1 Second													
-6≥	0.00	24,090	706	0.487	0.158	0.355	0.543	250	229	0.353	0.427	0.221	0.460
-5	0.00	38,454	1,479	0.459	0.170	0.371	0.620	254	308	0.398	0.334	0.268	0.484
-4	0.00	23,183	903	0.467	0.157	0.376	0.561	309	316	0.400	0.336	0.264	0.523
-3	0.00	35,668	737	0.464	0.164	0.372	0.505	313	353	0.396	0.338	0.266	0.490
-2	0.01	36,747	1,369	0.466	0.149	0.385	0.516	248	355	0.462	0.192	0.347	0.506
-1	1.09	10,181	1,165	0.500	0.032	0.468	0.501	123	275	0.504	0.098	0.398	0.498
0	97.79	5,685	940	0.502	0.022	0.475	0.495	75	190	0.514	0.082	0.404	0.501
1	1.09	11,045	1,231	0.503	0.031	0.466	0.496	113	267	0.506	0.097	0.397	0.502
2	0.01	39,908	1,726	0.473	0.134	0.393	0.534	206	339	0.474	0.172	0.354	0.512
3	0.00	24,609	885	0.442	0.178	0.380	0.397	297	329	0.397	0.324	0.279	0.478
4	0.00	32,698	1,736	0.472	0.106	0.422	0.696	289	271	0.411	0.318	0.271	0.506
5	0.00	25,573	463	0.457	0.176	0.367	0.523	386	310	0.387	0.341	0.272	0.472
6≤	0.00	41,202	993	0.439	0.212	0.349	0.647	350	228	0.354	0.431	0.215	0.474
10 Millisecond													
-6≥	0.00	1,463.0	37.8	0.538	0.190	0.272	0.468	21.9	11.1	0.435	0.325	0.240	0.498
-5	0.00	1,958.4	69.5	0.425	0.292	0.283	0.595	50.4	27.6	0.485	0.242	0.273	0.497
-4	0.00	1,947.5	42.7	0.417	0.188	0.395	0.531	108.1	53.4	0.494	0.234	0.272	0.532
-3	0.00	995.5	42.9	0.462	0.160	0.378	0.598	81.9	59.0	0.492	0.211	0.297	0.536
-2	0.00	1,718.7	57.3	0.499	0.123	0.378	0.535	57.4	48.0	0.498	0.146	0.357	0.543
-1	0.15	401.5	35.1	0.544	0.022	0.434	0.496	16.1	20.2	0.510	0.078	0.412	0.519
0.00	99.70	56.8	9.4	0.540	0.017	0.443	0.493	0.6	1.8	0.549	0.067	0.384	0.502
1	0.15	517.2	45.7	0.545	0.021	0.434	0.499	13.1	14.3	0.505	0.067	0.428	0.518
2	0.00	4,325.2	87.9	0.500	0.125	0.376	0.534	51.6	34.4	0.498	0.130	0.372	0.539
3	0.00	2,468.9	78.4	0.491	0.166	0.344	0.574	63.7	39.3	0.481	0.205	0.313	0.528
4	0.00	3,650.6	50.9	0.548	0.093	0.359	0.528	57.5	41.2	0.461	0.247	0.291	0.516
5	0.00	3,397.2	107.0	0.509	0.135	0.356	0.524	42.3	30.8	0.439	0.274	0.288	0.555
6≤	0.00	1,950.6	44.2	0.464	0.194	0.342	0.599	15.5	12.8	0.392	0.352	0.256	0.499

Note: The sample is divided into 13 groups based on change in cross-market bid-ask spreads measured in the number of ticks as shown in the first column. The top panel presents the activity for 1 second interval and the bottom panel for 10 milliseconds interval preceding the cross-market spread change. Columns on the left relate ES Futures Spread to SPY ETF activity whereas the columns on the right relate SPY ETF spreads and ES Futures activity in the immediately preceding interval. Columns New Order, Trade, Cancel, OI (order imbalance) map the liquidity supply, liquidity demand, liquidity withdrawal, and order imbalance variables, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 6: Cross-Asset Market Spreads VAR with Order Flow

	Panel A: 1 Second				Panel B: 10 Millisecond			
	Baseline		Volatile		Baseline		Volatile	
	500 ETF	Future	ETF	Future	ETF	Future	ETF	Future
Within Market								
ΔS_{-1}	−0.738***	−0.775***	−0.727***	−0.772***	−0.453***	−0.553***	−0.414***	−0.536***
ΔS_{-2}	−0.595***	−0.626***	−0.570***	−0.640***	−0.309***	−0.424***	−0.256***	−0.41***
ΔS_{-3}	−0.474***	−0.500***	−0.391***	−0.504***	−0.237***	−0.361***	−0.256***	−0.324***
ΔLS_{0}	−0.0444	−0.00528	−0.0614	−0.161***	−0.0181***	−0.00318	−0.0198***	−0.0118***
ΔLS_{-1}	−0.0187*	−0.0132***	−0.161***	−0.112***	−0.0105	−0.0229***	−0.0033	−0.0201***
ΔLS_{-2}	−0.0225	−0.0145***	−0.166**	−0.121***	−0.0185**	−0.0197***	−0.00919	−0.0236***
ΔLS_{-3}	−0.0113	−0.0119***	−0.224***	−0.122***	−0.00452	−0.0167***	−0.00793	−0.0194***
ΔLD_{0}	0.118	0.00926	0.391***	0.0378***	0.0591**	0.0285***	0.11***	0.0561***
ΔLD_{-1}	−0.121***	0.0107***	−0.0167	0.147***	0.0262	0.0252***	0.0599***	0.136***
ΔLD_{-2}	−0.0972***	0.0108***	0.174**	0.122***	0.0772**	0.0145***	0.0199	0.135***
ΔLD_{-3}	−0.0635**	0.0129***	0.155*	0.11***	0.0982***	0.0118*	0.00708	0.122***
ΔOI_{0}	0.000764	−0.0000912	−0.0269*	0.000825	−0.00259	0.000804	−0.000178	0.000254
ΔOL_{1}	−0.00204	0.000332	0.00724	0.00176	0.00637*	−0.000575	−0.000783	0.00178
ΔOL_{2}	−0.000774	−0.000122	0.0292	−0.00311	0.000663	−0.0000477	−0.00169	0.000782
ΔOL_{3}	0.000301	0.000667	0.0331	−0.000964	0.00642	−0.00115	−0.00143	−0.000478
ΔVolume_{0}	−0.00000901	−0.00995	0.00000464	−0.00872***	0.00278***	0.00939	0.00512***	−0.0417***
$\Delta \text{Volume}_{-1}$	0.0000529	0.00423***	−0.000528***	0.00426	−0.000966**	0.00664	−0.00252***	−0.0083
$\Delta \text{Volume}_{-2}$	0.00011*	0.00514***	−0.000194	0.00889**	−0.000814*	−0.00728	−0.00238***	−0.0139
$\Delta \text{Volume}_{-3}$	0.000147**	0.00604***	−0.000236	0.00932*	−0.00058	0.00071	−0.00207***	−0.00806
Cross Market								
ΔS_{0}	−0.0267		−0.0839***		−0.0203**		−0.0247***	
ΔS_{-1}	−0.00512	0.00246***	−0.0723***	0.000442	−0.00643	−0.000741	0.0143**	0.0028***
ΔS_{-2}	−0.000812	0.00176	−0.0843***	0.00147	−0.00877	−0.00227	−0.00625	0.00219*
ΔS_{-3}	0.00168	0.00238*	−0.0555***	−0.00199**	−0.00216	−0.0015	−0.000822	0.00118
ΔLS_{0}	−0.00526	−0.0123	0.00499	0.102***	0.00128	−0.00652*	0.00291	0.0111***
ΔLS_{-1}	0.00273	−0.0289***	0.0028	−0.0861***	−0.00444	−0.0144***	−0.00988*	−0.00815***
ΔLS_{-2}	−0.00117	−0.0263***	−0.028	−0.0914***	0.00262	−0.0233***	−0.00631	−0.00896**
ΔLS_{-3}	−0.0014	−0.0254***	−0.056	−0.0492*	0.00178	−0.0257***	−0.00695	−0.00926**
ΔLD_{0}	−0.00543	0.0311	−0.0189	0.0876***	0.00645	−0.00246	0.0238***	0.00401
ΔLD_{-1}	−0.0151***	−0.0449***	−0.0561**	−0.12***	−0.0133*	−0.0109	−0.0109	−0.0259***
ΔLD_{-2}	−0.0103	−0.037***	−0.0326	−0.148***	−0.00554	−0.0461***	−0.028**	−0.0353***
ΔLD_{-3}	−0.00847	−0.0391***	0.0239	−0.13***	−0.00585	−0.033	−0.029**	−0.0285***
ΔOI_{0}	−0.00125	−0.000138	0.00909	−0.000365	0.000265	0.00206	0.00162	−0.00188
ΔOL_{1}	0.0022	0.000101	0.00887	0.00195	0.00312	0.000265	0.00221	0.000639
ΔOL_{2}	0.00213	0.00298*	−0.00199	0.0046	−0.000787	0.002	0.00376	0.000964
ΔOL_{3}	0.00384	0.00255	0.00204	0.00257	−0.0000657	0.00326	0.00508	0.000523
ΔVolume_{0}	0.0126	0.0000383	−0.00685	0.0000657*	−0.0579*	−0.000032	0.181***	0.00000798
$\Delta \text{Volume}_{-1}$	−0.00342	−0.0000123	0.0446***	0.0000492	−0.0614**	−0.000164	0.112***	−0.000516***
$\Delta \text{Volume}_{-2}$	−0.0114**	−0.00000647	0.0183	−0.000029	−0.0682***	−0.000232	−0.00824	−0.000593***
$\Delta \text{Volume}_{-3}$	−0.00878*	−0.0000214	0.0188	−0.0000103	−0.037	−0.000103	−0.148***	−0.000307

Note: We present the cross-asset market spread SVAR. Panels A and B represent the 1 second and 10 milliseconds intervals, respectively. Within each panel regression coefficients for volatile and benchmark periods in ETF and futures market are shown. The dependent variable is spread. In addition to the lagged auto-correlation spread terms and lagged cross-correlation spread terms as explanatory variables (which are reported in the Table), additional order flow determinants of spreads include order imbalance, liquidity supply, liquidity demand, and volume (,000) as control variables (not included for brevity but available in an internet appendix). The asterisks ***,**, and *, indicate that coefficients are statistically significant at the 1%, 5% and 10% level, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 7.A: Impulse Response of Cross-Asset Market Spreads

	Panel A: 1 Second				Panel B: 10 Millisecond			
	Baseline		Volatile		Baseline		Volatile	
	ETF	Future	ETF	Future	ETF	Future	ETF	Future
S&P 500 Futures								
ΔLS	−0.000356	−0.002074***	−0.002011	−0.015484***	−0.001148	−0.006161***	−0.002233***	−0.006323***
ΔLD	−0.001701***	0.001626***	−0.003671***	0.010215***	−0.001258	0.005171***	−0.000204	0.019287***
ΔOI	0.000221	0.000061	0.002208	0.000583	0.001498	0.000013	0.001074	0.000723
ΔVolume	0.001006***	−0.000380***	0.001750	0.000437	−0.002559	0.000279	0.005472***	−0.001246***
S&P 500 ETF								
ΔLS	−0.002012***	−0.001490***	−0.004832***	−0.000192	−0.003025***	−0.002901***	−0.002048	−0.000379
ΔLD	−0.000677	−0.000428***	0.007107***	−0.001338***	0.002053***	−0.000474	0.006901***	−0.001571***
ΔOI	−0.000195	−0.000001	−0.001113	0.000151	0.001534	0.000411	−0.000256	−0.000111
ΔVolume	−0.000388	−0.000143	0.005550***	−0.001076***	−0.000588	0.000358	−0.000922	−0.001228***

Note: Impulse response of cross-asset market spreads to order flow. Panel A and Panel B represent the 1 second and 10 millisecond intervals, respectively. Within each panel regression coefficients for volatile and baseline periods in ETF and futures market are shown. The dependent variable is spread. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks *** indicate that coefficients are statistically significant at 1% level.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 7.B: Impulse Response of Cross-Asset Market Spreads with NBBO

	Panel A: 1 Second			
	Baseline		Volatile	
	ETF	Future	ETF	Future
S&P 500 Futures				
ΔLS Outside NBBO	−0.000423	0.000826***	−0.001646	0.006968***
ΔLS at NBBO	−0.000145	−0.002674***	−0.000630	−0.008402***
ΔLD	0.000236	0.000214	0.001486	−0.003424***
ΔLW Outside NBBO	0.001003***	0.005409***	−0.001790	0.008767***
ΔOI	0.000179	0.000048	−0.001248	−0.000791
ΔVolume	−0.000418	0.000184	−0.000741	0.000321
S&P 500 ETF				
ΔLS Outside NBBO	0.001508***	0.000542***	0.005270***	−0.001125***
ΔLS at NBBO	−0.000490	0.000100	−0.000259	0.001256***
ΔLD	0.000414	0.000616***	−0.002043	0.000161
ΔLW Outside NBBO	0.002212***	0.000291	0.006767***	0.002568***
ΔOI	0.000294	0.000373	0.000436	0.000258
ΔVolume	−0.000508	−0.000045	−0.006657***	0.001389***

Note: Impulse response of cross-asset market price spreads to order flow. Panel A and Panel B represent the 1 second, respectively. Within each panel regression coefficients for volatile and baseline periods in ETF and futures market are shown. The dependent variable is price return. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks ***,**, and *, indicate that coefficients are statistically significant at the 1%, 5% and 10% level, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 8: Impulse Response of Cross-Asset Market Price Returns

	Panel A: 1 Second				Panel B: 10 Millisecond			
	Baseline		Volatile		Baseline		Volatile	
	ETF	Future	ETF	Future	ETF	Future	ETF	Future
S&P 500 Futures								
ΔLS	−0.0000000059	−0.000000093	−0.000001***	−0.000001***	−0.00000011	0.000000049	0.000000082	−0.000000017
ΔLD	−0.00000016	0.000000091	−0.0000017***	−0.0000016***	0.000000009***	0.00000022***	−0.00000036***	−0.00000042***
ΔOI	0.000015***	0.000018***	0.000040***	0.000043***	0.00000061***	0.0000035***	0.0000016***	0.0000053***
ΔVolume	0.00000023***	0.0000003	−0.00000013	−0.000000041	0.00000004	−0.000000035	−0.0000000033	0.00000026***
S&P 500 ETF								
ΔLS	−0.000000087	−0.00000018	0.00000067***	0.00000052***	0.000000028	−0.000000055	−0.000000013	−0.000000031
ΔLD	−0.00000016	−0.00000035***	−0.0000012***	−0.0000013***	−0.000000022	−0.0000002	−0.000000022	−0.00000028**
ΔOI	0.000008***	0.000007***	0.000020***	0.000016***	0.0000013***	0.0000015***	0.000002***	0.0000016***
ΔVolume	−0.000000048	−0.0000004***	0.00000068***	−0.000000055	−0.0000000054	−0.000000066	−0.00000004	−0.00000034***

Note: Impulse response of cross-asset market price returns to order flow. Panel A and Panel B represent the 1 second and 10 millisecond intervals, respectively. Within each panel regression coefficients for volatile and baseline periods in ETF and futures market are shown. The dependent variable is price return. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks ***,**, and *, indicate that coefficients are statistically significant at the 1%, 5% and 10% level, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 9.A: Impact of Order Flow on Levels of Price Correlation

Correlation		S&P 500 ETF							S&P 500 Future						
of Returns	Frequency(%)	Spread	Volume	Messages	New Order	Trade	Cancel	OI	Spread	Volume	Messages	New Order	Trade	Cancel	OI
1 Second															
1.00 – 0.90	0.96	1.000	20,666	2,418	0.495	0.054	0.451	0.503	1.061	221	478	0.483	0.157	0.360	0.516
0.90 – 0.80	4.62	1.002	14,849	1,819	0.498	0.039	0.463	0.497	1.031	172	388	0.499	0.119	0.382	0.508
0.80 – 0.70	10.23	1.018	10,397	1,467	0.500	0.029	0.471	0.493	1.017	137	334	0.511	0.087	0.402	0.503
0.70 – 0.60	14.97	1.017	7,652	1,217	0.501	0.025	0.473	0.492	1.013	106	269	0.513	0.080	0.407	0.500
0.60 – 0.50	15.76	1.017	5,797	1,019	0.502	0.022	0.475	0.493	1.011	82	215	0.514	0.078	0.408	0.498
0.50 – 0.40	14.83	1.015	4,369	825	0.503	0.020	0.477	0.494	1.012	61	164	0.515	0.078	0.407	0.498
0.40 – 0.30	12.95	1.024	3,516	694	0.503	0.019	0.478	0.496	1.015	50	129	0.515	0.080	0.405	0.500
0.30 – 0.20	9.80	1.026	2,933	592	0.504	0.017	0.479	0.497	1.017	40	103	0.516	0.080	0.403	0.500
0.20 – 0.10	7.30	1.026	2,515	504	0.504	0.017	0.479	0.501	1.018	34	82	0.515	0.083	0.402	0.502
0.10 – 0.00	4.56	1.060	2,292	442	0.505	0.017	0.478	0.499	1.020	29	68	0.514	0.088	0.399	0.502
0.00–-1.00	4.02	1.058	1,991	397	0.504	0.017	0.480	0.504	1.024	24	59	0.512	0.086	0.402	0.510
10 Millisecond															
1.00 – 0.90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.90 – 0.80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.80 – 0.70	0.00	1.000	0.0	0.5	0.480	0.018	0.502	0.696	1.000	0.07	0.06	0.367	0.133	0.500	0.333
0.70 – 0.60	0.01	1.000	15.7	3.4	0.516	0.006	0.477	0.549	1.062	0.06	0.36	0.523	0.014	0.463	0.427
0.60 – 0.50	0.01	1.000	53.4	4.9	0.521	0.006	0.474	0.518	1.020	0.74	0.83	0.509	0.041	0.451	0.560
0.50 – 0.40	0.06	1.004	66.1	6.9	0.549	0.017	0.434	0.505	1.012	0.81	1.39	0.556	0.051	0.393	0.542
0.40 – 0.30	1.01	1.000	92.9	12.5	0.548	0.024	0.427	0.495	1.031	1.08	2.32	0.558	0.076	0.366	0.508
0.30 – 0.20	9.11	1.000	84.5	12.6	0.548	0.021	0.431	0.494	1.021	1.04	2.48	0.553	0.071	0.376	0.508
0.20 – 0.10	44.30	1.011	66.1	10.9	0.544	0.017	0.439	0.492	1.013	0.92	2.33	0.549	0.065	0.386	0.503
0.10 – 0.00	39.02	1.039	47.8	7.9	0.535	0.016	0.449	0.493	1.015	0.64	1.57	0.545	0.069	0.386	0.499
0.00–-1.00	6.48	1.018	17.8	4.0	0.519	0.011	0.470	0.501	1.028	0.21	0.57	0.532	0.068	0.401	0.502

Note: Variable of focus is the price correlation between the ETF and Futures market. The top panel is divided into 1 second intervals throughout the entire trading day into 11 groups based on the level of correlation between the ETF and futures asset prices changes during that second. The groups range from very high correlation of +0.90 to +1 to opposite price movements in the last correlation group of 0 to -1. The groups are defined analogously in the bottom Panel for 10 millisecond intervals. Average SPY ETF in the given correlation bucket is shown on the left and that for ES Futures is on the right. Columns New Order, Trade, Cancel, OI map the liquidity supply, liquidity demand, liquidity withdrawal, and order imbalance variables, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 9.B: Impact of Order Flow on Changes in Price Correlation

Δ Correlation		S&P 500 ETF							S&P 500 Future						
of Returns	Frequency(%)	Spread	Volume	Messages	New Order	Trade	Cancel	OI	Spread	Volume	Messages	New Order	Trade	Cancel	OI
1 Second															
-0.06≥	1.94	1.032	3,848	695	0.494	0.019	0.468	0.498	1.017	45	141	0.468	0.066	0.372	0.499
-0.05	0.90	1.034	4,442	788	0.494	0.020	0.468	0.497	1.014	53	166	0.466	0.070	0.368	0.501
-0.04	1.52	1.033	4,634	865	0.493	0.021	0.466	0.496	1.015	61	186	0.464	0.071	0.367	0.500
-0.03	2.67	1.030	5,149	930	0.492	0.022	0.466	0.495	1.012	66	206	0.466	0.071	0.367	0.499
-0.02	5.00	1.033	5,543	1,009	0.491	0.023	0.465	0.493	1.013	73	230	0.465	0.070	0.370	0.500
-0.01	13.74	1.026	5,575	1,048	0.491	0.023	0.465	0.494	1.013	73	240	0.464	0.072	0.368	0.502
0.00	48.59	1.017	4,478	900	0.492	0.022	0.466	0.496	1.018	56	197	0.466	0.070	0.369	0.501
0.01	13.81	1.023	6,476	1,071	0.491	0.023	0.464	0.494	1.014	91	248	0.466	0.070	0.369	0.499
0.02	4.92	1.027	8,455	1,092	0.492	0.022	0.464	0.494	1.014	125	253	0.467	0.070	0.369	0.500
0.03	2.58	1.028	9,710	1,061	0.493	0.022	0.464	0.495	1.013	146	238	0.465	0.072	0.368	0.502
0.04	1.49	1.013	11,172	1,003	0.495	0.021	0.465	0.495	1.014	162	219	0.470	0.070	0.368	0.499
0.05	0.86	1.027	11,797	997	0.495	0.020	0.465	0.499	1.017	182	215	0.469	0.071	0.366	0.500
0.06≤	1.97	1.011	20,057	1,068	0.497	0.019	0.464	0.498	1.020	298	226	0.471	0.069	0.369	0.498
10 Millisecond															
-0.06≥	0.79	1.060	719.6	42.7	0.503	0.024	0.433	0.495	1.029	10.02	12.96	0.480	0.047	0.373	0.506
-0.05	0.07	1.140	827.9	50.2	0.504	0.030	0.422	0.494	1.047	11.40	16.04	0.474	0.052	0.365	0.514
-0.04	0.10	1.139	770.3	45.3	0.505	0.030	0.422	0.497	1.050	9.70	13.95	0.470	0.052	0.362	0.515
-0.03	0.15	1.142	795.9	46.9	0.504	0.032	0.421	0.495	1.048	10.18	14.51	0.472	0.054	0.361	0.512
-0.02	0.58	1.069	552.6	35.3	0.500	0.025	0.433	0.493	1.028	9.10	10.91	0.477	0.047	0.373	0.506
-0.01	0.97	1.135	634.2	39.1	0.505	0.031	0.422	0.494	1.039	8.54	11.81	0.478	0.050	0.364	0.509
0.00	94.82	1.029	41.1	9.8	0.525	0.017	0.424	0.493	1.013	0.52	2.15	0.519	0.037	0.366	0.504
0.01	0.95	1.141	327.3	24.5	0.518	0.030	0.413	0.494	1.038	2.91	6.41	0.488	0.048	0.354	0.507
0.02	0.57	1.074	295.1	22.1	0.512	0.024	0.422	0.493	1.026	2.99	5.86	0.486	0.043	0.360	0.506
0.03	0.13	1.156	320.8	26.7	0.532	0.030	0.401	0.496	1.044	4.07	7.38	0.498	0.051	0.345	0.514
0.04	0.09	1.146	312.2	26.6	0.529	0.029	0.404	0.494	1.045	4.56	7.38	0.496	0.051	0.351	0.512
0.05	0.06	1.155	372.9	27.8	0.531	0.029	0.405	0.494	1.046	6.38	8.10	0.499	0.051	0.348	0.497
0.06≤	0.72	1.050	1303.2	54.5	0.507	0.022	0.432	0.494	1.030	28.35	20.80	0.489	0.052	0.370	0.504

Note: This table presents the analysis for changes in price correlation to supplement the results on levels of correlations in previous table. The 1 second and 10 millisecond panels are each divided into 11 groups from -0.06 decrease in correlation to +0.06 increase in correlation relative to the previous period.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 10: Impulse Response of Price Return Correlation

	Panel A: 1 Second		Panel B: 10 Millisecond	
	Baseline	Volatile	Baseline	Volatile
S&P 500 Futures				
ΔLS	−0.000834***	−0.000381***	−0.000054***	−0.000027***
ΔLD	0.001558***	0.001012***	0.000109***	0.000096***
ΔOI	−0.000157	0.000104	−0.000012	−0.000003
ΔVolume	0.005933***	0.004646***	0.000257***	0.000212***
S&P 500 ETF				
ΔLS	−0.000283***	−0.000799***	−0.0000073	−0.000021***
ΔLD	0.000500***	0.000393***	−0.000003	−0.0000046
ΔOI	−0.000059	0.000058	−0.0000032	0.000003
ΔVolume	0.001666***	0.001266***	0.000112***	0.000077***

Note: Impulse response of cross-asset market return correlation to order flow. Panel A and Panel B represent the 1 second and 10 millisecond intervals, respectively. Within each panel regression coefficients for volatile and baseline periods are shown. The dependent variable is ETF-futures return correlation. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks *** indicate that coefficients are statistically significant at 1% level.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table 11.A: The October 30 2014 NYSE SIP Disruption

	S&P 500 ETF							
Period	Returns(1s)	Spread	Volume	Messages	New Order	Trade	Cancel	OI
Pre - 1:07PM	5.076E-03	1.000	3,216	1,269	0.499	0.009	0.492	0.502
1:07PM - 1:34PM	1.524E-02	1.000	3,945	828	0.497	0.014	0.488	0.515
Post - 1:34PM	1.729E-04	1.000	3,890	854	0.499	0.016	0.485	0.494
	S&P 500 Future							
Period	Returns(1s)	Spread	Volume	Messages	New Order	Trade	Cancel	OI
Pre - 1:07PM	4.862E-03	1.004	69.4	244	0.434	0.084	0.482	0.490
1:07PM - 1:34PM	1.501E-02	1.007	74.0	162	0.416	0.117	0.467	0.457
Post - 1:34PM	4.338E-04	1.003	63.5	135	0.418	0.118	0.465	0.523

Note: SIP Outage Sample of 86.3 million messages over 23.4 thousand 1 second periods on the equity market SIP outage date of October 30, 2014. Variable definitions are same as Table 1. Averages for 1s windows.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis

Table 11.B: SIP Disruption: Impulse Response of Cross-Asset Market Spreads

	Pre - 1:07PM		1:07PM - 1:34PM		Post - 1:34PM	
	ETF	Future	ETF	Future	ETF	Future
S&P 500 Futures						
ΔLS	0.000380	−0.004783***	0.000418	−0.003164	−0.000576	−0.001809***
ΔLD	−0.000170	0.001105	−0.000348	−0.000950	−0.003465**	0.000928
ΔOI	0.002300	0.000411	0.000234	−0.000491	−0.000797	0.000096
ΔVolume	−0.001300	0.000732	−0.000180	0.000234	−0.000054	0.001846**
S&P 500 ETF						
ΔLS	0.000550	−0.003180***	0.000266	−0.000925	−0.000886	−0.001385**
ΔLD	−0.002600	−0.001315	−0.003187	0.000873	0.000384	−0.001351**
ΔOI	−0.000069	−0.000606	0.000436	−0.000342	0.000822	0.000512
ΔVolume	0.005600***	−0.000649	−0.002741	−0.000023	0.000829	0.000167

Note: Impulse response of cross-asset market spreads to order flow. Panel A and Panel B represent the 1 second and 10 millisecond intervals, respectively. Within each panel regression coefficients for volatile and baseline periods in ETF and futures market are shown. The dependent variable is spread. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks ***,**, and *, indicate that coefficients are statistically significant at the 1%, 5% and 10% level, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis

Table 11.C: SIP Disruption: Impulse Response of Cross-Asset Market Price Returns

	Pre - 1:07PM		1:07PM - 1:34PM		Post - 1:34PM	
	ETF	Future	ETF	Future	ETF	Future
S&P 500 Futures						
ΔLS	−0.0000002	0.0000002	−0.0000042***	−0.0000052**	−0.0000003	0.0000012
ΔLD	0.0000003	0.0000002	0.0000028***	0.0000030	0.0000001	0.0000002
ΔOI	0.0000160***	0.0000180***	0.0000120***	0.0000130***	0.0000110***	0.0000140***
ΔVolume	0.0000029***	0.0000031***	0.0000310***	0.0000350***	−0.0000004	−0.0000009
S&P 500 ETF						
ΔLS	−0.0000001	−0.0000001	−0.0000029***	−0.0000023	−0.0000007	−0.0000004
ΔLD	−0.0000001	−0.0000009	0.0000064***	0.0000055***	0.0000009**	−0.0000006
ΔOI	0.0000070***	0.0000071***	0.0000087***	0.0000066***	0.0000080***	−0.0000070***
ΔVolume	−0.0000002	0.0000005	0.0000048***	0.0000050***	0.0000004	−0.0000006

Note: Impulse response of cross-asset market price returns to order flow. Panel A and Panel B represent the 1 second and 10 millisecond intervals, respectively. Within each panel regression coefficients for volatile and baseline periods in ETF and futures market are shown. The dependent variable is price return. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks ***,**, and *, indicate that coefficients are statistically significant at the 1%, 5% and 10% level, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis

Table 11.D: SIP Disruption: Impulse Response of Price Return Correlation

	Pre - 1:07PM	1:07PM - 1:34PM	Post - 1:34PM
S&P 500 Futures			
ΔLS	-0.001265^{***}	-0.002207^{**}	-0.001454^{***}
ΔLD	0.002598^{***}	0.001684^{**}	0.002127^{***}
ΔOI	0.000186	0.001148	-0.000440
ΔVolume	0.004439^{***}	0.007774^{***}	0.00548^{***}
S&P 500 ETF			
ΔLS	-0.000650^{***}	-0.000118^{***}	-0.000963^{***}
ΔLD	0.000444^{**}	0.001091	0.000273
ΔOI	0.000009	0.000339	0.000389
ΔVolume	0.001498^{***}	-0.001096	0.001115^{***}

Note: Impulse response of cross-asset market return correlation to order flow. Panel A and Panel B represent the 1 second and 10 millisecond intervals, respectively. Within each panel regression coefficients for volatile and baseline periods are shown. The dependent variable is ETF-futures return correlation. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks ***,**, and *, indicate that coefficients are statistically significant at the 1%, 5% and 10% level, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis

Table 12.A: The May 6 2010 Flash Crash

	S&P 500 ETF							
Period	Returns(1s)	Spread	Volume	Message	New Order	Trade	Cancel	OI
Pre - 2:32PM	-1.467E-02	1.007	15,012	1,231	0.503	0.030	0.467	0.507
2:32PM - 2:45PM	-7.112E-01	1.065	69,008	4,051	0.491	0.043	0.467	0.517
2:45PM - 3:00PM	4.001E-01	1.360	50,418	2,422	0.480	0.076	0.444	0.488
Post - 3:00PM	4.743E-02	1.002	35,981	2,720	0.493	0.043	0.464	0.490
	S&P 500 Future							
Period	Returns(1s)	Spread	Volume	Message	New Order	Trade	Cancel	OI
Pre - 2:32PM	-1.461E-02	1.000	152	296	0.500	0.081	0.419	0.507
2:32PM - 2:45PM	-8.056E-01	1.017	611	1,026	0.484	0.107	0.409	0.479
2:45PM - 3:00PM	5.007E-01	1.297	631	354	0.411	0.286	0.303	0.514
Post - 3:00PM	4.435E-02	1.011	304	487	0.481	0.133	0.387	0.521

Note: Flash Crash Sample of 502 million messages over 23.4 thousand 1 second periods on the flash crash day of May 6, 2010 that started with an unusually large order in futures market. Variable definitions are same as Table 1. Averages for 1s windows.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis

Table 12.B: Flash Crash: Impulse Response of Cross-Asset Market Spreads

	Pre - 2:32PM		2:32PM - 2:45PM		2:45PM - 3:00PM		Post - 3:00PM	
	ETF	Future	ETF	Future	ETF	Future	ETF	Future
S&P 500 Futures								
ΔLS	−0.001249***	−0.000364***	−0.003126	−0.001654	−0.805900	−0.190956***	−0.025000**	−0.014664***
ΔLD	0.001630	0.000352**	0.001019***	−0.000431	−0.902900	−0.019505**	0.017900	0.000821
ΔOI	0.000138	0.000074	−0.002513	−0.003944	1.287400	−0.000429**	−0.000700	−0.001258
ΔVolume	−0.000059	0.001644***	0.000723	−0.002512	0.848600	0.059039	0.000790	0.003419
S&P 500 ETF								
ΔLS	−0.000729**	−0.000130	0.002661	0.002108	−1.746300***	−0.010146	0.004900	−0.000864
ΔLD	0.000828**	0.000162	0.003744	0.000120	1.856600***	−0.004348	−0.001400	−0.002240
ΔOI	0.000154	0.000003	0.000840	0.001315	1.212900***	0.028815	0.009200	0.000590
ΔVolume	−0.000134	−0.000540***	0.010960***	−0.000210	−0.076300	−0.042171	0.009100	−0.002697

Note: Impulse response of cross-asset market spreads to order flow. Panel A and Panel B represent the 1 second and 10 millisecond intervals, respectively. Within each panel regression coefficients for volatile and baseline periods in ETF and futures market are shown. The dependent variable is spread. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks ***,**, and *, indicate that coefficients are statistically significant at the 1%, 5% and 10% level, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis

Table 12.C: Flash Crash: Impulse Response of Cross-Asset Market Price Returns

	Pre - 2:32PM		2:32PM - 2:45PM		2:45PM - 3:00PM		Post - 3:00PM	
	ETF	Future	ETF	Future	ETF	Future	ETF	Future
S&P 500 Futures								
ΔLS	0.000002***	0.000003***	0.000035***	0.000023***	−0.000041	−0.000008	0.000010***	0.000006
ΔLD	−0.000002	−0.000002***	−0.000025***	−0.000013*	−0.000048	−0.000035	−0.000007	−0.000007
ΔOI	0.000030***	0.000034***	0.000110***	0.000101***	0.000180**	0.000172***	0.000093***	0.000097***
ΔVolume	−0.000005***	−0.000005***	−0.000023***	−0.000011	0.000090	0.000030	−0.000005	−0.000004
S&P 500 ETF								
ΔLS	0.000000	0.000002	−0.000000	0.000001	−0.000088	−0.000042	0.000006	0.000006
ΔLD	0.000001	0.000001	−0.000021***	−0.000020**	0.000044	0.000000	−0.000004	0.000001
ΔOI	0.000018***	0.000020***	0.000071***	0.000062***	0.000101	0.000036	0.000069***	0.000044***
ΔVolume	0.000006***	0.000004***	0.000024**	0.000019**	−0.000089	−0.000007**	−0.000004	−0.000006

Note: Impulse response of cross-asset market price returns to order flow. Panel A and Panel B represent the 1 second and 10 millisecond intervals, respectively. Within each panel regression coefficients for volatile and baseline periods in ETF and futures market are shown. The dependent variable is price return. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks ***,**, and *, indicate that coefficients are statistically significant at the 1%, 5% and 10% level, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis

Table 12.D: Flash Crash: Impulse Response of Price Return Correlation

	Pre - 2:32PM	2:32PM - 2:45PM	2:45PM - 3:00PM	Post - 3:00PM
S&P 500 Futures				
ΔLS	-0.001467^{***}	-0.001011	-0.000378	-0.001199^{***}
ΔLD	0.002430^{***}	0.000231	-0.000258	0.000791^{**}
ΔOI	-0.000097	0.000013	-0.001420	0.000037
ΔVolume	0.00532^{***}	0.001898^{***}	0.002092^{***}	0.002006^{***}
S&P 500 ETF				
ΔLS	-0.001100^{***}	-0.000685	0.000724	-0.000852^{**}
ΔLD	0.000890^{***}	0.000007	-0.000302	-0.000106
ΔOI	0.000310	0.000124	0.000319	0.000121
ΔVolume	0.001355^{***}	0.001027	-0.000902	0.000881^{***}

Note: Impulse response of cross-asset market return correlation to order flow. Panel A and Panel B represent the 1 second and 10 millisecond intervals, respectively. Within each panel regression coefficients for volatile and baseline periods are shown. The dependent variable is ETF-futures return correlation. Explanatory variables are changes in within-market and cross-markets liquidity supply, liquidity demand, order imbalance, and volume from futures and ETF market. The asterisks ***,**, and *, indicate that coefficients are statistically significant at the 1%, 5% and 10% level, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis

Table A.1: Empirical Sample Dates

Volatile Dates	Baseline Dates	Volatility
3/18/2015	3/26/2014	E
1/8/2016	1/9/2015	E
10/2/2015	10/10/2014	E
1/27/2016	2/4/2015	E
6/24/2016	6/26/2015	E
8/24/2015	8/25/2014	U
8/21/2015	8/22/2014	U
9/1/2015	9/2/2014	U
1/13/2016	1/14/2016	U
1/20/2016	1/21/2015	U

Note: E: anticipated macroeconomic news announcements associated with volatility, U: unexpected volatility with no anticipated macroeconomic news announcements.
Source: Authors' creation.

Table A.2: Within-Market Spread and Order Flow at 1 Second

		S&P 500 ETF											
ETF		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1	97.82	5,638	939	0.502	0.022	0.476	0.495	5,696	940	0.502	0.022	0.475	0.495
2	1.94	7,628	1,052	0.505	0.024	0.471	0.497	6,715	1,041	0.502	0.026	0.472	0.497
3	0.06	17,660	906	0.491	0.072	0.438	0.499	16,377	901	0.488	0.071	0.441	0.492
4	0.04	20,689	984	0.485	0.092	0.423	0.516	22,659	896	0.489	0.090	0.422	0.526
5	0.02	17,981	956	0.480	0.105	0.416	0.542	23,407	931	0.481	0.102	0.416	0.542
6	0.02	19,233	802	0.485	0.100	0.415	0.511	17,950	902	0.480	0.100	0.421	0.514
7	0.01	21,523	778	0.487	0.078	0.434	0.535	17,373	843	0.484	0.081	0.436	0.547
8	0.01	24,973	792	0.479	0.122	0.398	0.501	26,807	667	0.479	0.111	0.410	0.502
9	0.01	20,451	785	0.491	0.093	0.417	0.501	13,994	785	0.481	0.103	0.416	0.472
10	0.01	21,030	1,339	0.476	0.119	0.405	0.564	22,138	1,023	0.479	0.106	0.415	0.554
10<	0.06	22,762	726	0.474	0.123	0.403	0.528	18,753	707	0.471	0.133	0.396	0.531
		S&P 500 Future											
Future		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1	98.44	77	194	0.513	0.083	0.404	0.501	78	195	0.513	0.083	0.403	0.501
2	1.52	105	193	0.522	0.087	0.391	0.498	68	181	0.500	0.093	0.407	0.505
3	0.03	221	295	0.415	0.263	0.323	0.481	178	252	0.406	0.275	0.319	0.469
4	0.01	398	198	0.354	0.428	0.218	0.487	231	173	0.382	0.389	0.229	0.512
5	0.00	301	139	0.335	0.440	0.226	0.403	228	103	0.334	0.472	0.194	0.357
6	0.00	428	295	0.287	0.555	0.158	0.363	311	202	0.287	0.541	0.172	0.461
7	0.00	388	159	0.257	0.594	0.148	0.605	357	137	0.249	0.619	0.132	0.561
8	0.00	519	96	0.348	0.484	0.168	0.565	117	167	0.312	0.573	0.116	0.466
9	0.00	555	137	0.234	0.642	0.124	0.313	453	147	0.218	0.755	0.027	0.594
10	0.00	766	208	0.250	0.577	0.173	0.519	393	191	0.319	0.518	0.162	0.508
10<	0.00	342	186	0.263	0.606	0.131	0.527	257	175	0.285	0.560	0.155	0.408

Note: The sample is divided into 11 groups based on size of bid-ask spreads measured in the number of ticks as shown in the first column, at the end of the current interval. Two separate panels are presented for the SPY ETF and ES futures market, respectively, for within market order flow at 1 second before (columns on the left) and after (columns on the right) the given spread is observed. Columns New Order, Trade, Cancel, OI map the liquidity supply, liquidity demand, liquidity withdrawal, and order imbalance variables, respectively, during the current interval (pre-activity) and next interval (post-activity).
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table A.3: Within-Market Spread and Order Flow at 10 Millisecond

		S&P 500 ETF											
ETF		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1	97.84	51	9.16	0.540	0.016	0.444	0.493	55	9.29	0.540	0.016	0.444	0.493
2	1.92	103	10.97	0.560	0.019	0.421	0.499	73	10.47	0.556	0.019	0.425	0.498
3	0.06	339	14.11	0.541	0.069	0.390	0.511	211	11.17	0.539	0.070	0.391	0.509
4	0.04	264	10.80	0.541	0.078	0.381	0.516	197	10.22	0.538	0.081	0.381	0.516
5	0.02	293	9.89	0.537	0.089	0.374	0.526	196	9.31	0.540	0.088	0.373	0.523
6	0.02	195	8.20	0.539	0.092	0.369	0.501	185	8.09	0.537	0.093	0.370	0.504
7	0.01	265	8.73	0.524	0.086	0.390	0.525	161	8.82	0.522	0.088	0.390	0.528
8	0.01	162	7.75	0.533	0.095	0.372	0.521	158	7.69	0.527	0.097	0.376	0.525
9	0.01	203	7.45	0.532	0.090	0.378	0.498	168	7.28	0.535	0.093	0.373	0.491
10	0.01	224	8.52	0.528	0.102	0.370	0.488	168	8.13	0.525	0.104	0.371	0.491
10<	0.06	254	7.77	0.514	0.128	0.358	0.528	222	7.85	0.515	0.126	0.359	0.527
		S&P 500 Future											
Future		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1	98.44	1	1.93	0.548	0.067	0.385	0.502	1	1.93	0.548	0.067	0.385	0.502
2	1.52	2	2.95	0.560	0.067	0.374	0.510	1	2.49	0.554	0.071	0.375	0.510
3	0.03	5	4.11	0.471	0.224	0.304	0.482	2	3.60	0.468	0.225	0.307	0.478
4	0.01	7	3.45	0.425	0.350	0.225	0.451	3	2.75	0.416	0.363	0.221	0.454
5	0.00	8	2.84	0.388	0.397	0.214	0.448	4	2.42	0.391	0.392	0.217	0.447
6	0.00	19	5.25	0.439	0.371	0.189	0.455	4	5.35	0.406	0.395	0.199	0.487
7	0.00	10	2.55	0.345	0.482	0.173	0.495	5	2.47	0.346	0.500	0.155	0.414
8	0.00	7	2.90	0.401	0.407	0.192	0.497	5	2.60	0.382	0.407	0.211	0.513
9	0.00	8	2.01	0.285	0.519	0.197	0.431	2	1.81	0.323	0.489	0.188	0.474
10	0.00	15	2.39	0.293	0.581	0.127	0.525	4	1.77	0.325	0.548	0.127	0.468
10<	0.00	14	2.98	0.308	0.479	0.213	0.467	4	2.79	0.261	0.520	0.220	0.476

Note: The sample is divided into 11 groups based on size of bid-ask spreads measured in the number of ticks as shown in the first column. Two separate panels are presented for the SPY ETF and ES futures market, respectively, for within market order flow at 10 milliseconds before (columns on the left) and after (columns on the right) the given spread is observed. Columns New Order, Trade, Cancel, OI map the liquidity supply, liquidity demand, liquidity withdrawal, and order imbalance variables, respectively.

Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table A.4: Cross-Asset Market Spread and Order Flow at 1 Second

		S&P 500 ETF											
Futures		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1	98.44	5,730	944	0.502	0.022	0.475	0.495	5,741	944	0.502	0.022	0.475	0.495
2	1.52	9,859	1,106	0.502	0.032	0.466	0.498	9,106	1056	0.500	0.032	0.467	0.501
3	0.03	29,912	1,494	0.479	0.105	0.416	0.532	29,514	1407	0.478	0.106	0.416	0.534
4	0.01	23,157	1,137	0.468	0.133	0.399	0.551	33,612	1098	0.463	0.138	0.400	0.564
5	0.00	19,660	743	0.462	0.148	0.391	0.587	23,600	775	0.462	0.181	0.358	0.601
6	0.00	29,507	1,397	0.463	0.144	0.393	0.603	33,887	1167	0.469	0.142	0.389	0.588
7	0.00	29,567	885	0.441	0.222	0.337	0.617	37,873	685	0.450	0.238	0.313	0.605
8	0.00	33,945	583	0.425	0.290	0.285	0.466	28,977	621	0.481	0.327	0.192	0.471
9	0.00	64,672	796	0.489	0.065	0.446	0.905	22,166	855	0.481	0.092	0.427	0.769
10	0.00	11,641	1,592	0.474	0.111	0.415	0.877	23,648	886	0.490	0.072	0.438	0.878
10<	0.00	62,899	722	0.410	0.308	0.282	0.458	41,889	726	0.440	0.259	0.301	0.339
		S&P 500 Future											
ETF		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1	97.82	76	192	0.514	0.082	0.404	0.501	76	192	0.514	0.082	0.404	0.501
2	1.94	96	251	0.503	0.100	0.397	0.497	98	252	0.502	0.101	0.397	0.495
3	0.06	201	293	0.448	0.219	0.334	0.507	183	290	0.446	0.224	0.330	0.513
4	0.04	211	330	0.424	0.280	0.297	0.511	257	274	0.418	0.279	0.302	0.516
5	0.02	261	289	0.383	0.347	0.270	0.498	258	278	0.395	0.335	0.270	0.487
6	0.02	273	264	0.400	0.319	0.281	0.481	244	295	0.396	0.335	0.269	0.458
7	0.01	282	327	0.387	0.339	0.274	0.475	338	342	0.397	0.328	0.275	0.479
8	0.01	314	315	0.375	0.381	0.244	0.496	282	278	0.377	0.374	0.249	0.510
9	0.01	330	277	0.370	0.396	0.234	0.514	366	309	0.365	0.394	0.241	0.503
10	0.01	290	326	0.350	0.434	0.216	0.443	362	305	0.327	0.455	0.218	0.437
10<	0.06	318	222	0.355	0.420	0.225	0.483	258	218	0.357	0.419	0.225	0.483

Note: The sample is divided into 11 groups based on size of cross-market bid-ask spreads measured in the number of ticks for as shown in the first column. The top panel has ES Futures Spread and SPY ETF activity whereas the bottom plan has SPY ETF spreads and ES Futures activity for the 1 second interval before (columns on the left) and after (columns on the right) the given spread is observed. Columns New Order, Trade, Cancel, OI map the liquidity supply, liquidity demand, liquidity withdrawal, and order imbalance variables, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.

Table A.5: Cross-Asset Market Spread and Order Flow at 10 Millisecond

		S&P 500 ETF											
Futures		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1	98.44	57	9.4	0.540	0.017	0.443	0.493	57	9.4	0.540	0.017	0.443	0.493
2	1.52	106	13.8	0.555	0.027	0.418	0.498	96	12.8	0.555	0.027	0.418	0.498
3	0.03	456	17.5	0.530	0.094	0.376	0.523	351	16.2	0.530	0.096	0.374	0.522
4	0.01	344	12.9	0.509	0.136	0.355	0.551	288	11.6	0.509	0.134	0.357	0.542
5	0.00	432	9.7	0.503	0.175	0.321	0.560	303	8.8	0.508	0.167	0.324	0.557
6	0.00	589	22.3	0.482	0.163	0.355	0.570	418	17.7	0.482	0.157	0.360	0.591
7	0.00	333	9.6	0.501	0.159	0.340	0.672	227	8.9	0.493	0.172	0.335	0.678
8	0.00	303	12.0	0.482	0.211	0.306	0.517	312	11.4	0.473	0.212	0.316	0.514
9	0.00	462	13.3	0.500	0.175	0.325	0.542	283	13.9	0.442	0.239	0.319	0.568
10	0.00	378	13.0	0.488	0.120	0.391	0.590	355	11.0	0.513	0.124	0.363	0.572
10<	0.00	494	13.3	0.461	0.241	0.298	0.544	491	12.8	0.469	0.240	0.291	0.532
		S&P 500 Future											
ETF		Pre Activity						Post Activity					
Spread	Frequency(%)	Volume	Messages	New Order	Trade	Cancel	OI	Volume	Messages	New Order	Trade	Cancel	OI
1	97.84	0.70	1.86	0.548	0.066	0.386	0.502	0.73	1.89	0.548	0.066	0.386	0.502
2	1.92	1.26	2.36	0.543	0.076	0.381	0.507	0.97	2.44	0.548	0.077	0.375	0.506
3	0.06	4.11	4.44	0.503	0.183	0.314	0.529	2.97	3.75	0.502	0.183	0.314	0.530
4	0.04	3.39	3.69	0.493	0.220	0.286	0.522	2.81	3.40	0.493	0.221	0.286	0.523
5	0.02	3.16	3.53	0.477	0.246	0.277	0.500	3.11	3.39	0.477	0.245	0.277	0.498
6	0.02	2.88	2.95	0.467	0.268	0.265	0.489	2.76	2.92	0.466	0.269	0.265	0.493
7	0.01	4.25	3.54	0.451	0.300	0.249	0.505	4.38	3.37	0.455	0.296	0.250	0.503
8	0.01	3.38	2.97	0.457	0.290	0.254	0.507	3.16	2.80	0.460	0.287	0.254	0.497
9	0.01	3.16	2.91	0.453	0.292	0.255	0.520	3.38	2.89	0.456	0.286	0.258	0.523
10	0.01	3.17	2.86	0.461	0.314	0.225	0.484	2.67	2.83	0.457	0.313	0.230	0.485
10<	0.06	3.06	2.48	0.434	0.338	0.229	0.501	2.87	2.38	0.435	0.336	0.229	0.500

Note: The sample is divided into 11 groups based on size of cross-market bid-ask spreads measured in the number of ticks for as shown in the first column. The top panel has ES Futures Spread and SPY ETF activity whereas the bottom plan has SPY ETF spreads and ES Futures activity for the 10 milliseconds interval before (columns on the left) and after (columns on the right) the given spread is observed. Columns New Order, Trade, Cancel, OI map the liquidity supply, liquidity demand, liquidity withdrawal, and order imbalance variables, respectively.
Source: E-mini S&P 500 Futures front month contract, and SPDR S&P 500 ETF from Thesys Technologies, Authors' analysis.