Market Return Around the Clock: A Puzzle☆

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This version: August 18, 2020

Abstract

We study how the excess market return depends on the time of the day using E-mini S&P 500 futures that are actively traded for almost 24 hours. Strikingly, four hours around European open account for the entire average market return. This period's returns are consistently positive in every year, have an extra-high Sharpe ratio, and exceed transaction costs. Average returns are close to zero during the remaining 20 hours. High returns around European open are consistent with European investors processing overnight information and thus resolving uncertainty. Indeed, uncertainty reflected by VIX futures prices increases overnight and plummets around European open. These results shed light on how equity premium is formed at the micro level.

JEL Classification: G12, G13, G14

Keywords: Market return, uncertainty resolution, intraday data, index futures

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☆We greatly appreciate comments from Kenneth Ahern, Ferhat Akbas, Hank Bessembinder, Vincent Bogousslavsky, Peter Ciampi, Ryan Israelsen, Naveen Khanna, Paul Koch, Dermot Murphy, Neil Pearson, Jeff Pontiff, Angelo Ranaldo, Dominik Roesch, Pavel Savor, Andrei Simonov, Guofu Zhou, Haoxiang Zhu, Eric Zitzewitz and seminar participants at Michigan State University, University of Illinois at Chicago, and the Virtual Finance Seminar. We also thank CME DataMine and TickData for providing intraday futures data. We thank Julia Dougherty and Suzanna Emelio for editorial assistance. We are responsible for all remaining errors. Suggestions and comments are welcome.

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1. Introduction

When are market returns positive? We study how the excess market return as reflected by the S&P 500 index changes over day and night. E-mini S&P 500 futures are actively traded at night, and their returns equal the excess returns on the S&P 500 index.[1] Figure 1 shows how average cumulative returns of E-mini futures depend on time of day. The E-mini trading session starts at 6:00 p.m. Eastern Time (ET) and spans almost 24 hours. Average returns during one period stand out. After flat returns in the first part of the overnight session, the cumulative returns rapidly increase between 11:30 pm and 3:30 am and become flat again afterwards. These four hours have a 7.6% annualized return. Asian markets close and European markets open during this "EU-open" period: deep night in the U.S., late afternoon in Asia, and early morning in Europe. In contrast, total returns for the rest of the day are only -0.8% p.a. and are flat for the entire day except for a zig-zag around US close: returns rapidly increase but then revert with a small net effect. These return patterns are puzzling because most theories imply positive average returns through a day.

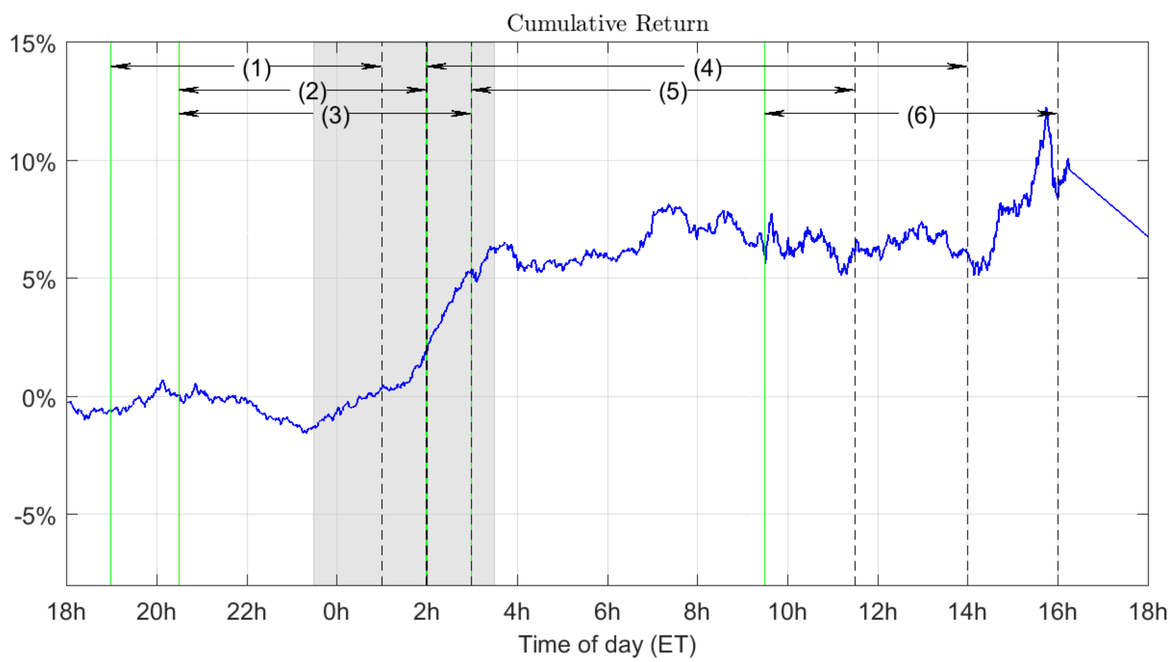

Figure 1. Annualized average cumulative log returns for S&P 500 E-mini futures as a function of time of the day in Eastern Time (ET). Line arrows denote open and close times for major equity markets (Japan, China, Hong Kong, Frankfurt, London, and the U.S.). Between 4:15 and 6:00 pm, the market only trades for a short 30-minute session. Hence, we use a single return from 4:15 to 6:00 pm and connect the two prices with a straight line. EU-open period is in grey. Annualized return equals period return times 252, the number of trading days in a year. The sample period is from January 2004 to July 2018.

[1] S&P 500 E-mini futures return is commonly used to measure the excess market return. Unlike raw index returns, returns of S&P futures already reflect the risk-free rate and dividends. Hasbrouck (2003) shows that E-mini futures lead the spot index and account for most price discovery.

It is known that the close-to-open period generates most of the daily return, one of the biggest unsolved puzzles about market returns.[2] Huseyin Gulen said it well: "We can show that the gap exists, but at this point we don't know exactly why" (New York Times, 2/2/2018). We help resolve this puzzle. First, we use data unavailable to prior researchers – high-frequency returns from the overnight period – and show that the returns are positive *only* during the EU-open, which is deep night for US investors. Second, because positive returns are concentrated in only one period, we can reject most explanations for the positive overnight returns. The only explanation that is consistent with our results is uncertainty resolution, an idea of broad, general interest (e.g., Epstein and Zin, 1989; Dixit and Pindyck, 1994; Bloom, 2009).

EU-open returns are very consistent; a 7.6% annualized return has a *t*-statistic of 6.4, much higher than conventional significance levels. Returns are positive in every calendar year, month, and weekday and are robust to dropping special days such as FOMC, other macro news, and turn-of-the-month days. To alleviate microstructure concerns, average returns computed with trade prices and quote midpoints are indistinguishable. Following the literature, expected returns are computed as an average of realized returns from a single time series and thus could be sensitive to a sample period. But statistical tests, including the Bonferroni procedure and the reality check of White (2000) confirm that EU-open results are not due to data mining – picking the best performing period of the day. In contrast, cumulative return is insignificant during the rest of the day and almost all its sub-intervals – an equally puzzling fact. Consider a one-hour moving window that shifts every minute through a day. The moving window *t*-statistic for average returns reaches six during EU-open while returns for only three other hourly intervals briefly touch a 1% significance threshold: around 7:30 pm, 7:00 am, and 3:00 pm. EU-open is the only significant period if the window is extended to four hours. It has the highest Sharpe ratio and statistical significance, while the other notable pattern – the up-and-down returns around US close – is barely significant and has a small net effect on average returns.

After carefully documenting the EU-open puzzle, we try to explain it. Asian market close and European open are the main recurrent events during this four-hour period. The change in daylight saving time serves as an exogenous shock that helps us distinguish between Asia's and Europe's impacts. Since Asia does not observe daylight saving time, Asian time shifts by one-hour relative to Europe for about half a year. The run-up in price during EU-open stays unchanged in

[2] Cliff, Cooper, and Gulen (2008), Kelly and Clark (2011), Berkman, Koch, Tuttle, and Zhang (2012) among others.

European time but shifts in Asian time. Trading volume also shifts in Asian time. Thus, the Asian close does not cause the EU-open price run-up, European markets do.

Are high EU-open returns due to overnight illiquidity or conventional risks? Most futures are illiquid outside of regular trading hours, but E-mini S&P futures are an exception. Not only are they by far the most liquid index product during regular hours but they also remain among top futures during the less active Asian and European sessions.[3] In a typical EU-open period, $14 billion of S&P index exposure is traded with 3.3 trades per second. Trading costs remain low; the bid-ask spread is 0.017% on average and is almost always one tick. About $5.6 million is available for immediate execution at the best bid or ask. Thus, even large investors can take liquidity fast and at low cost. Similarly, higher expected returns should be associated with higher risk. But EU-open appears less risky than the rest of the day by simple risk measures: return standard deviation is 3.9 times lower; maximum daily loss and drawdown are much lower; annualized Sharpe ratio is 1.67 versus zero. EU-open returns are positively skewed, which many investors prefer, while return skewness is negative during the rest of the day.

Out of all the explanations that we consider, uncertainty resolution comes closest to explaining the EU-open puzzle. Price uncertainty arises because market price deviates from fundamental value, an unobserved price that reflects all public information after proper risk adjustment. Quoting Black (1986): "All estimates of value are noisy, so we can never know how far away price is from value." High uncertainty makes an asset riskier and causes a price discount. Uncertainty is relatively low during the US and European sessions as many large investors keep the E-mini price close to value. But uncertainty can accumulate during Asian hours as fewer investors are active.[4] Processing information is hard work that requires a critical mass of investors. The accumulated uncertainty is resolved during EU-open: European investors return to the market and push E-mini price towards value. They independently process any price-relevant public information from the overnight period.

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[3] CME Group (2017) estimates that E-mini S&P futures are the 4th most actively traded index future in Asia with an average daily turnover of $7.1T during Asian hours, surpassed only by Hang Seng ($15.5T ADV), KOSPI 200 ($12T), and OSE Nikkei index futures ($8.2T). E-mini's trading volume jumps five-fold once the European session starts.

[4] Price uncertainty can be due to the size gap between the Asian economy and its asset management industry. Asia is the world's economic powerhouse and its news matters. The International Monetary Fund reports that Asia contributes $31.6T toward the world's GDP, more than Europe ($21.8T) and North America ($24.4T) in 2019. But few large investors operate in this time zone: the 2017 survey shows that AUM in Asia is $4,58T, or 2.75 and 6.7 times lower than in Europe and the U.S., respectively.

Why does price increase as uncertainty is resolved? Consider a stylized example where the economy's future is determined by a coin toss. After talking to Asian investors, you estimate that the probability of tossing heads, a good state, is uniformly distributed between 0.4 and 0.8, hence the uncertainty. You gather extra information from European investors and conclude that the probability of heads is 0.6; uncertainty is resolved. A risk-averse investor will pay more, or require lower return, for the 0.6 gamble than for the 0.4–0.8 one. Thus, uncertainty resolution causes price to increase. This stylized example can be adopted to the EU-open case. Each investor receives a small independent signal about fundamental value. During the Asian session, price reflects only Asian investors' signals while Europeans sleep. During EU-open, all signals are incorporated into the price, uncertainty is resolved, and price increases. Several theories formalize the uncertainty discount. Hu, Pan, Wang, and Zhu (2019) argue that uncertainty resolution causes the pre-FOMC drift. In their model, when uncertainty is resolved, prices increase, but volatility can stay low. Similarly, Hong and Wang (2000) and Easley and O'Hara (2004) argue that the more information prices reflect, the smaller the price discount is relative to value.

Several tests support the uncertainty resolution hypothesis. *First*, many European investors are absent from the market on EU holidays, a quasi-exogenous shock to the number of investors who resolve uncertainty. Thus, uncertainty is not being resolved during EU-open on EU holidays. Indeed, EU-open returns are slightly *negative* when EU markets are closed but the US market is open; positive returns shift to the rest of the European session, when US investors arrive and resolve uncertainty. We next directly test how EU-open returns are related to uncertainty measures. *Second*, EU-open returns are higher if more information arrives overnight, and high uncertainty is accumulated as measured by high Asian volatility or volume. *Third*, EU-open returns are also higher after uncertainty increases as reflected by popular daily measures: VIX index, VSTOXX implied volatility on EURO STOXX 50 index, the news-based economic policy uncertainty index of Baker, Bloom, and Davis (2016), and Twitter-based economic uncertainty and market uncertainty indices of Baker, Bloom, Davis, and Renault (2020). *Also*, a model that predicts EU-open return out-of-sample with just two uncertainty variables – VIX change and Asian volatility – shows that EU-open returns are only positive when prior uncertainty is high. *Fourth*, VIX futures let us track uncertainty around the clock. Cumulative returns for VIX futures increase through the Asian session, indicating increased uncertainty. This is the only intraday period when uncertainty increases. The positive VIX trend reverses at exactly the start of EU-open; cumulative returns are highly negative during EU-open. Uncertainty, as reflected by VIX future prices, rapidly declines during the second half of EU-open, while cumulative market return and realized volatility rapidly increase. Market return moves in sync with uncertainty. Similarly, although EU-open volatility is relatively low, volatility and returns move in sync within this period: as cumulative returns accelerate in the second half of EU-open so does volatility. The final two tests indirectly support the uncertainty hypothesis. The trade size is lowest during Asian hours and increases through EU-open indicating that large investors return during this time. *Finally*, a variance ratio test shows that prices are 14% less efficient during the Asian session than after EU-open, and the price efficiency steadily increases through EU-open as price converges to value.

A trading strategy, which we study next, lets us conclude that the return patterns are not just some artifact of illiquidity or limits to arbitrage. A simple strategy buys futures right before EU-open and closes the position after its end. Despite trading twice a day, it remains profitable net of conservative estimates of trading costs – exchange fees, commissions, and the bid-ask spread. The average after-cost return is statistically significant, and its Sharpe ratio exceeds that of the buy-and-hold alternative. This naïve strategy can be greatly improved by only trading when expected EU-open returns are higher than average. Per-day profitability more than doubles while costs remain the same resulting in a 4.6% after-cost annual return with a Sharpe ratio of 1.2. This conditional strategy predicts EU-open returns out-of-sample with variables motivated by uncertainty resolution: VIX daily change and Asian volatility. An impressive 6.6% out-of-sample R^2_{OS} is 2.5 times higher than for comparable models in the literature (e.g., Gao, Han, Li, and Zhou, 2018). The estimated capacity for these strategies is about $9 billion, with average after-cost profits of about $50 million per year. The EU-open anomaly can also help long-term investors reduce their trading costs: they should time their trades and buy before (sell after) EU-open.

We next consider inventory risk. Liquidity providers, who are risk-averse and have limited capital, absorb customer order flow and must be compensated for holding these suboptimal portfolios. Perhaps night-averse investors sell at US close and repurchase their positions at EU-open. Inventory risk seems intuitive and plausible, but on a closer look, its predictions about average returns are rejected by the data. First, market return should be high during the entire Asian session to compensate dealers for the risk, but the pre-EU-open returns are instead slightly negative. Second, we take advantage of the time trend in Asian volume, which increased four-fold from 2004 to 2018. As Asia becomes more active, the inventory premium should decrease, but EU-open returns change little. Third, weekends are an extended non-trading period, but have slightly lower EU-open returns than weekdays. Fourth, if no inventory shock occurs at US close, then high EU-open returns should disappear. But average EU-open returns remain large for the subsample with zero order imbalance. Finally, in a direct horse-race, inventory risk is subsumed by uncertainty resolution. Order imbalance from US close cease to predict EU-open return once we control for change in VIX, which remains highly significant.

Other explanations also receive little support in the data. Perhaps close-to-open returns are positive because most news arrives at night. Market-moving US news, such as earnings and many macro news, are released shortly before US open or after US close. But EU-open occurs while US is in deep night, hours away from these news intensive periods. Even most EU macro news are at or after EU-open's end. Perhaps European investors are optimistic and buy at the open. But EU-open returns do not depend on sentiment measures. Market return can be higher to compensate investors for interest and margin payments incurred overnight. Carry costs are incurred every calendar day and thus are higher over weekends, but weekend EU-open returns are slightly lower.

This paper contributes to several literatures. Building on earlier literature on close-to-open returns for individual stocks, Cliff, Cooper, and Gulen (2008) show that the overnight period generates most of the daily return.[5] They conclude that "the effect is driven in part by high opening prices which subsequently decline." Berkman, Koch, Tuttle, and Zhang (2012) argue that large price changes trigger retail investor attention, who drive up the opening price the next day.[6] These studies do not observe prices at night. In contrast, we show that overnight return is positive *only* during EU-open, which casts new light on how results in the prior studies are interpreted. We explain the positive overnight return puzzle with uncertainty resolution and show that uncertainty is a major micro-level determinant of market return complementing the growing literature on the

[5] Wood, McInish, and Ord (1985) report higher overnight returns for six months in 1971/72, while Rogalski (1984) and Harris (1986) find lower returns in daily data for 1974-1984 and intraday data for 1983, respectively. Smirlock and Starks (1986) show that overnight returns in the DJIA are lower in 1974-1983 and are higher in 1963-1974.

[6] A growing literature studies conditional properties of day-night returns. Heston, Korajczyk, and Sadka (2010) show that some stocks tend to perform better during specific half hours of the trading day. Lou, Polk, and Skouras (2019) show substantial differences in the cross-section of intraday versus overnight average returns: some anomalies, such as momentum, earn their premium entirely during the overnight period, while other anomalies, e.g. betting against beta, have a negative premium overnight. Hendershott, Livdan, and Rösch (2020) study day-night CAPM. Bogousslavsky (2019) shows a substantial variation in the cross-section of returns within the trading day. Akbas, Boehmer, Jiang, and Koch (2020) study how differences in opinion measured by overnight reversal predict market returns. Gao et al. (2018) show that overnight return for SPY ETF predicts its last half-hour return during regular trading. These studies focus on return cross-section and conditional market returns, while we focus on average market return and use detailed overnight data.

return implications of market uncertainty at longer horizons including Anderson, Ghysels, and Juergens (2009), Bollerslev, Tauchen, and Zhou (2009), Segal, Shaliastovich, and Yaron (2015), and Manela and Moreira (2017). European investors receive little attention in prior literature but play a crucial role in resolving uncertainty during EU-open. In concurrent work, Boyarchenko, Larsen, and Whelan (2020) argue that inventory risk explains the positive market returns during the hour before the London opens because these returns are within the bid-ask spread, and because they observe a reversal between US close and London open. By focusing on just one hour they miss most of the market return as returns are large through the entire EU-open, which explains why EU-open returns are positive after trading costs. We focus on the *average* market return and show that it is consistent with uncertainty resolution. Boyarchenko et al. (2020) complement our results by focusing on the return *reversals*, which could be related to inventory risk (e.g., Nagel, 2012), but as we show the latter cannot explain the average EU-open returns. We also provide stylized facts about average returns that theories of market closures should aim to explain (e.g., Slezak, 1994; Longstaff, 1995; Admati and Pfleiderer, 1989; Foster and Viswanathan, 1990; Hong and Wang, 2000). Finally, we contribute to the literature on event-based anomalies for market return, such as the pre-FOMC drift (e.g., Lucca and Moench, 2015; Savor and Wilson, 2013, 2014; and Boguth, Grégoire, and Martineau, 2019), by identifying an equally puzzling anomaly.[7]

The paper is organized as follows. Section 2 describes the data and methodology. Section 3 explores how market returns depend on the time of day. Section 4 discusses and tests potential explanations. Section 5 concludes.

2. Data, methodology, and trading regimes

Our initial data for E-mini S&P 500 futures (ticker ES) consist of 10-second bars for trades and quotes obtained from TickData. Trade bars are standard and include open, high, low, and close prices as well as the number of trades and trading volume. Quote bars include closing best bid and ask and their sizes. Trade data span the period from January 1998 to July 2018. Because TickData only has quote data starting from January 2010, we extend that period to 2006 with similar data

[7] In our sample, EU-open makes 7.6% return per year versus 2.9% for the pre-FOMC drift – less per event, but more in aggregate. Other related references include: Stroud and Johannes (2014) study how E-mini S&P return volatility changes around the clock, but they do not study average returns. Muravyev and Ni (2020) show that option returns are negative overnight and positive intraday. We extend their results by showing that overnight VIX futures returns are negative primarily during EU-open. Ranaldo (2009), and Breedon and Ranaldo (2013) study currency returns around the clock, and their pattern differs greatly from what we find for equities.

obtained directly from CME DataMine. The contract has four expiration months per year: March, June, September, and December. We use data for the front month contract until it reaches eight days to expiration and then switch into the next available contract. This procedure follows the industry rollover practice and ensures that the most actively traded contract is used. We exclude days when the market is closed, or when the trading session is cut short due to a US holiday. For most of our tests, the data are aggregated to one-minute or lower frequency.

We compute one-minute log returns, using the last price for every minute. Log returns can easily be aggregated to any required horizon. For easier interpretation, we annualize average return by multiplying period return by 252, the number of trading days in a typical year. For robustness, we confirm that our results are similar if we use *simple* returns instead of *log* returns. Also, the results are almost identical if returns are computed with quote midpoints instead or trade prices (see Figure IA.1 in the Internet Appendix). Futures returns offer two practical advantages for studies of equity risk premium: (1) they are already in excess of the risk-free rate, and (2) they already account for the dividends paid by S&P 500 index, unlike for example SPY.

The notional value of E-mini S&P 500 futures contract is $50 times the value of the S&P 500 stock index. If S&P 500 is 1566, which is the sample average, then one E-mini S&P 500 contract represents a $78,300 exposure. We multiply the number of contracts traded by the contract's notional value to obtain the dollar volume. Following the literature, we compute the realized volatility from ten-second log returns and then annualize it. The relative bid-ask spread is the difference between ask and bid prices scaled by the quote midpoint. Market depth is the average of the number of contracts available at the best bid and best ask.

The E-mini S&P is the most important contract linked to the S&P 500 index due to its high liquidity and embedded leverage. Other S&P 500 alternatives are less popular. The SPDR S&P 500 ETF, or SPY, was launched in 1993 and currently boasts $260 billion AUM. In 2012, the E-mini S&P traded $142 billion per day versus $18.5 billion for SPY. SPY only trades during regular and extended US trading hours: 6:00 am to 8:00 pm, which excludes EU-open. Similarly, a median stock in S&P 500 index trades only 17 times in the after-hour session (Gregoire and Martineau, 2019); thus, studying EU-open returns for individual stocks is not feasible. Regular, or "big," S&P 500 futures (ticker SP) were popular until early 2000s, but rarely trade now. Other popular index futures contracts, such as E-mini Nasdaq 100 and E-mini DJIA, have the same trading hours as E-mini S&P futures but are less liquid. We confirm that EU-open results hold for them.

The E-mini contract has a long history. The Chicago Board of Trade (CBOT) introduced evening floor trading in the late 1980s to address international demand for Treasury futures during non-US trading hours. But many traders were tired by trading into the night. Thus, CME Group launched a fully-electronic platform Globex on June 25, 1992, as a low impact means of providing after-hours market coverage. It runs on the technology by Reuters and began with three currency products and one Treasury note product, but quickly expanded into other assets. The E-mini S&P 500 futures contract was launched on September 9, 1997, after the value of the existing S&P contract became too large for many traders. The contracts are traded exclusively on Globex and referred to as E-mini: "mini" because their size is only 1/5 of that for regular S&P 500 contracts, and "E" because they are only traded electronically. Business soared after CME allowed customers to trade directly in the Globex system, without having to go through a broker in 2000. The Globex average daily volume exceeded one million contracts in 2002 and physical pit volume for the regular S&P futures in 2004. Table IA.2 in the Internet Appendix shows how trading activity for Asian, European, and US sessions changed from 1998 to 2018. Asian share of trades jumped from 0.07% of all trades in 2002 to 1.28% in 2004, or 18 times over the two years.

CME gradually extended the Globex trading hours. Until July 2003, the trading started at 1:00 am and only covered a portion of EU-open. To study market returns around the clock, we start our sample in 2004 after trading day was extended to almost 24-hour and overnight liquidity increased. Table IA.3 shows that extending our sample to an earlier period does not change the main results. Currently, the E-mini contract trades 22:45 hours a day, 5 days a week. CME comes online on Sunday at 6:00 pm and closes on Friday at 5:00 pm ET. The continuous trading session spans from 6:00 pm to 4:15 pm the following day, followed by a 15-minute trading halt from 4:15 to 4:30 pm and a 30-minute trading session from 4:30 to 5:00 pm. Our empirical analysis covers the entire 24-hour day including the period from the end of one continuous session at 4:15 pm to the start of the next continuous session at 6:00 pm.

A trading day can informally be split into three distinct regimes – Asian (6:00 pm to 2:00 am), European (2:00 am to 9:30 am), and US (9:30 am to 4:15 pm) – which differ in investor composition, news geography, and trading activity.[8] The technology stays the same, as E-minis

[8] Throughout the paper, all times are Eastern Time (ET). More precisely, ET is Eastern Standard Time (EST) when daylight saving time (DST) is not observed (winter) and is Eastern Daylight Time (EDT) when DST is observed (summer). When not specified otherwise, all our figures and tables refer to EST season. E.g., Figure 1 corresponds to winter. During summer (EDT), trading hours of Asian (but not European) exchanges would shift by one hour ahead.

are traded exclusively at GLOBEX. A new CME session starts at 6:00 pm ET. In winter, Japan opens at 7:00 pm, followed by China and Hong Kong at 8:30 pm. Their stock exchanges remain open until 1:00, 2:00, and 3:00 am, respectively. During the Asian session, most economic news is about the Asian region and local investors dominate this session's trading. The European session starts at 2:00 am, when Frankfurt and Eurex open, followed by London and several Euronext markets at 3:00 am. The European session lasts until 9:30 am, when the US stock market opens although most European markets remain open until 11:30 am. Finally, the US session starts at 9:30 am and ends at 4:15 pm, 15 minutes after the US equity market closes, making the end of the continuous session. Table 2 summarizes the trading hours for major equity markets. The next trading day begins at 6:00 pm; but most US investors have already left by then. Table IA.1 reports return distribution and other metrics for these informal regimes and other intervals of interest.

3. Market return around the clock

In this section, we study how average market return computed from prices of E-mini S&P 500 futures depend on the time of day and document the EU-open puzzle. Before exploring returns, we describe how the trading environment changes over the day. Market conditions differ greatly across the three informal regimes: Asia, Europe, and the U.S., defined in the previous section. Table 3 and Figure 2 show that trading activity and liquidity are expectedly lowest during the Asian session, higher during the European hours, and most active during the US session. Volatility is 56% lower for Asia and 37% lower for Europe than for US. Thus, the entire Asian session only contributes 14% to daily return variance. Volatility and volume are driven by many factors: risk-sharing, noise trading – price discovery is only one of them. Trading volume also varies greatly. Per-hour volume during Asia is 5.5 times lower than for Europe, which in turn is 8.4 times lower than for US. Asian volume is relatively low compared to volatility because the S&P 500 index depends on the Asian economy, but Asian traders constitute a relatively small share of all investors. Indeed, the average trade size, a measure of investor clientele, is lowest during Asian hours (3.4 contracts), with 44% and 132% higher size during European and US hours. Perhaps investors who trade E-mini during Asian hours are smaller on average.

Although the Asian session is the least active, it is still abundantly liquid in absolute terms with 121 trades and $36 million traded per minute, or $17 billion for the entire 8-hour session. Thus, even large investors can seamlessly execute their trades. The bid-ask spread is almost always one tick: 0.25 index points, or $12.50. The average spread is 0.017%. The market is deep with 65 future contracts at the best bid (or ask), or about $5.6 million available for immediate execution. EU-open is even more liquid as it spans part of the European session.

We next describe our main result. Figure 1 shows how returns for E-mini S&P futures accumulate minute-by-minute through a trading day. We report annualized returns that can also be viewed as an average future's price scaled to zero at the origin. The results are puzzling. Cumulative return remains flat (fluctuates between -1% and 1% p.a.) over the Asian session and is slightly negative, -1.3% p.a., by 11:30 pm ET. But then the trend reverses; cumulative return starts to increase slowly and then accelerates shortly before European exchanges (Frankfurt, Amsterdam) open at 2:00 am. The price run-up stops shortly after London opens at 3:00 am. During this four-hour period, cumulative return increases from -1.3% to 6.3% for a 7.6% p.a. total return. After London open, the return fluctuates between 2% and -2% p.a. during the European and most of the US sessions. The volatility spike at US open does not affect the average return. During the last two hours of the US session, cumulative return increases by 4% p.a.; but due to huge volatility the return is only statistically significant for few minutes at 3:45 pm (see Figure 3). This pre-close price increase almost completely reverses between US close at 4:15 pm and 6:00 pm re-open.

Overall, 100% of the average market return is concentrated in the four hours between 11:30 pm and 3:30 am ET. The start of "EU-open," 11:30 pm, corresponds to 4:30 am German Time, when the first European investors wake up and check the market. The positive return trend accelerates around 1:30 am – 7:30 am in Europe – when many traders arrive to the office before European open at 8:00 am. Returns continue to increase as London investors check-in. The second half of EU-open, when European markets open, accounts for 5.4% of the 7.6% total return. Returns increase steadily without zig-zags. Figure 3 explores the statistical significance of cumulative returns during EU-open, US close, and the two periods in between by showing minute-by-minute confidence intervals. Cumulative return becomes statistically significant 40 minutes into EU-open and strongly significant around 1:30 am. US close returns become significant for a brief 20-minute period around 3:45 pm but then revert to insignificant. We focus on the best performing period – EU-open – and leave the other interesting period – US close – for future research.

Table 1 compares EU-open return with the rest of the day, from 3:30 am to 11:30 pm. Average EU-open return is 7.60% p.a. with a *t*-statistic of 6.35, while rest-of-day return is -0.8%

with a *t*-statistic of -0.17.[9] EU-open appears less risky than the rest of the day by simple risk measures. First, return standard deviation is 4.55% p.a., or 3.9 times lower than for the rest of the day. Skewness is positive (1.64), indicating that large positive returns are more likely than large negative returns, a property that many investors prefer. In contrast, return skewness is negative for the rest of the day (-0.99) and the entire day (-0.42).[10] The largest loss and gain are comparable for EU-open, -3.95% and 4.52% per day, and less extreme than -13.07% and 8.47% for the rest of the day. Thus, EU-open returns are not driven by few outliers. A trading strategy based on EU-open has a maximum drawdown of only 8% versus 66.4%. Kurtosis is the only measure that is higher for EU-open, 57 versus 16. Fourth return moments are similar, but EU-open volatility is much lower, and kurtosis is proportional to their ratio. EU-open is usually quiet with occasional large price moves. Figure IA.3 shows how cumulative returns for EU-open accrue over the sample period in an almost straight line, while rest-of-day returns do not grow despite high volatility. Of course, these measures may not fully reflect the risks associated with EU-open.

Figures 1 and 3 identify the important parts of the day; a moving window analysis let us discover more granular return patterns. We compute average return and its *t*-statistic over a one-hour window, then move it by one minute and repeat. Figure 4 shows the centered moving-average *t*-statistic over the day. For the negative returns side, *t*-statistic touches a 5% threshold an hour before EU-open and briefly at 9:00 am, when US macro news is released. The one-hour *t*-statistic reaches six during EU-open while only two other hourly intervals briefly touch a 1% threshold: around 7:30 pm and 7:00 am. The period before US close at 3:00 pm crosses the 5% level but does not reach 1% significance. If the window is extended to four hours, EU-open remains the only significant period with a *t*-statistic of greater than six. EU-open stands out among all one- or four-hour windows, while other intervals are not robustly significant.

Following the literature, we assume that expected market return is computed as an average of realized returns. Average returns can be sample-dependent due to high return variance and time variation in expected returns. But average EU-open returns are extremely robust and consistent. Table 4 reports EU-open returns by year and compares them to the rest of the day. EU-open returns

[9] Throughout the paper, *t*-statistics account for heteroscedasticity and autocorrelation as in Newey and West (1986). To account for the high kurtosis of return distribution, we also compute *t*-statistics with block bootstrap. Our results become more significant with bootstrapped *t*-statistics: e.g., a 1% threshold *t*-statistic of 2.30 instead of conventional 2.58. Thus, we prefer Newey-West *t*-statistics as they are more conservative in our case.

[10] This difference between EU-open and rest-of-day return skewness can be useful for reconciling why return skewness is negative for aggregate stock market and positive for individual stocks (e.g., Albuquerque, 2012).

are positive and economically significant in every year. The lowest EU-open returns are 2.25% in 2017 and 4.53% p.a. in 2004 (t-statistics of 1.63 and 2.06); the highest returns are 16.24% in 2009 and 13.52% in 2015. Average EU-open returns during the first and the second part of the sample match almost exactly. These consistently positive returns help alleviate data mining and other related concerns that average EU-open returns could be unrepresentative. Section 4.4 uses appropriate statistical procedures to further test for data mining. EU-open return volatility follows trends in the overall market volatility; it is highest in 2008 and lowest in 2017. In contrast, returns during the rest of the day vary a lot and are statistically significant in only in 2017 (t-statistic of 2.5). In contrast, EU-open return is significant in 9 out of 15 years. The lowest rest-of-day return is expectedly in 2008 (-55.8%), while EU-open return is 9.8% in this turbulent year. Figure 5 shows cumulative return and its t-statistic for a two-year moving average over the sample period. EU-open returns are significant in almost any two-year window. The financial crisis does not affect them apart from higher volatility. Rest-of-day returns are rarely significant; the only exceptions are two instances in 2014 (at a 5% significance level) and one instance in 2018 (close to a 1% level).

Other robustness tests confirm that EU-open returns are consistently positive. First, Table 5 reports EU-open returns by the calendar month and weekday. Return is highest on Tuesdays (9.64%) and lowest on Mondays, night after a weekend (4.83%). It is lowest in January and October (3.11% and 3.75%) and highest in December and February (11.96% and 11.49%). EU-open return volatility is similar during all weekdays and calendar months except for higher volatility in October due to the 2008 financial crisis. Second, EU-open results are robust to excluding (1) days with important macro or earnings announcements, (2) triple witching days, (3) days when S&P futures hit up/down limits, and (4) the turn of the month period. Interestingly, on the FOMC announcement days, the famous pre-FOMC drift starts shortly into EU-open after zero return during Asian hours (Figure IA.11). Thus, EU-open is an important period for other anomalies. Third, EU-open return decreases from 7.6% to 6.6% if we exclude its five highest observations. Thus, EU-open results are not driven by few outliers. Also, Figure IA.1 shows that the trajectories for average cumulative returns over a day computed from quote midpoints and trading prices are indistinguishable. Thus, the EU-open puzzle is not due to bid-ask bounce or other microstructure concerns. Finally, Figure IA.2 shows that cumulative average returns for E-mini Nasdaq 100 and Dow index futures have very similar patterns as E-mini S&P returns in Figure

3. Table IA.3 shows that EU-open returns remain positive during the pre-2004 period that includes the bursting of the Dot-com bubble even though trading was only possible during a part of the EU-open period.[11]

4. Explaining the puzzle

In this section, we try to explain the EU-open puzzle. We first show that the puzzle is attributed to European open rather than Asian close (Section 4.1). We then consider several explanations including uncertainty resolution (Section 4.2), limits to arbitrage (Section 4.3), data mining (Section 4.4), inventory risk (Section 4.5), news arrival, investor sentiment, algorithmic trading, and carry costs (Section 4.6). Uncertainty resolution is most consistent with the data.

4.1 Asian close versus European open

To understand why EU-open returns are high, we first distinguish the impact of two main recurrent events during this period: European markets open (in Frankfurt and then London) and Asian markets close. Intuitively, the Asian session is less active, and thus Asian close is less likely to affect EU-open returns. The challenge is that China closes at 2:00 am exactly when Frankfurt opens, and London opens and Hong Kong closes at 3:00 am. Table 2 reports opening and closing times for major equity markets. Daylight saving time (DST) – an exogenous shock to relative time between Europe and Asia – helps us separate the effects of Asian close and European open. Asia does not observe DST, while Europe and the US do. DST in Europe extends from the last Sunday in March to the last Sunday in October. DST in Europe and the US overlap except for a brief period of three to four weeks, depending on a year.

From the US perspective, Hong Kong market closes at 3:00 am ET in winter but at 2:00 am in summer. If Asia is important, the EU-open price run-up will shift with the shift in Asian time relative to Europe and US. To test this hypothesis, Figure 6 compares cumulative returns and trading volume around EU-open during winter and summer DST periods in Europe. In European time, cumulative returns and volume are very similar for the two subperiods. The EU-open return pattern is constant in European time and thus shifts in Asian time. Indeed, when the same graphs are presented in Asian time, you can clearly see a one-hour shift between summer and winter for return and volume. The volume pattern "lives" in European time, which is consistent with the

[11] Also, in the pre-2004 sample, we find that returns are highly negative around US open during the burst of the dot-com bubble in 2001-2002, which could be attributed to margin selling by US investors.

European session being more liquid than the Asian session. We confirm that the shift in cumulative return and volume are highly statistically significant. This shift in the cumulative return clearly shows that European open and not Asian close drives the EU-open price run-up. This result encourages us to explore a special role that European investors play.

4.2 Uncertainty resolution

The uncertainty resolution hypothesis comes closest to explaining the EU-open puzzle. In short, European investors return to the market during EU-open after the night break, they process accumulated information, and thus resolve uncertainty, which in turn increases prices.

We first explain how uncertainty resolution affects prices. Price uncertainty quantifies how much market price deviates from fundamental value, the unobserved price that would reflect all public information after a proper risk-adjustment. Price can deviate from value as public information is not fully processed, and investors differ in their ability to process information. For example, annual reports contain an ocean of price-moving data that are impossible to interpret completely. By analogy, physics laws imply that an engine cannot transform energy into useful work at 100% efficiency. During the US and European sessions, many sophisticated investors are active and keep prices close to value. But uncertainty can accumulate during Asian hours with fewer active investors. A critical mass of investors is required to process information. Uncertainty is resolved during EU-open. Large European investors wake up, return to the market, and push E-mini price towards value. They independently process any price moving information accumulated overnight, which is much broader than just published news.

Uncertainty is priced because investors are risk-averse and rely on prices to choose their portfolios. Higher uncertainty makes an asset riskier as its price is further away from value, but investors cannot tell which way. Thus, investors require a price discount. Hu et al. (2019) formalize this intuition with a three-period model: a final payoff is paid in the last period and has a random variance. The value for the variance is revealed in the second period, hence uncertainty resolution. When uncertainty is being resolved not only do prices increase but volatility can stay low (propositions 1 and 2 in their paper). Their model is agnostic about how payoff's variance becomes more certain and can be extended to specify a channel for uncertainty resolution. In our case, the channel can be modeled by assuming that each investor receives a signal about value. During Asian hours, price reflects only Asian investors' signals while Europeans sleep. During EU-open, uncertainty is resolved as prices now reflect all signals. Individual signals are small and independent enough so that costs of waking up at night overweigh the benefits for EU investors. Prices increase because risk-averse investors are willing to pay more, or require lower expected return, when uncertainty about value decreases.

Relatedly, Easley and O'Hara (2004) study how total amount of information in the system affects asset prices. They show that a lower fraction of informed traders makes the stock riskier for both informed and uninformed investors increasing expected return. Expected return increases because when information is private, rather than public, uninformed investors cannot perfectly infer information from prices and require higher return. Hong and Wang (2000) study average returns, volatility, and volume around market closures that "can be broadly interpreted as periods when a subset of investors withdraws from the market." Prices increase endogenously as information asymmetry is resolved around market open. As market price deviates from value, uninformed investors are only willing to buy the asset at a discount. In both theories, the more information prices reflect, the smaller the price discount is relative to value.

We conduct seven tests that support the uncertainty resolution hypothesis. *First*, what if European investors are absent from the market during EU-open perhaps because they are on holiday? Unique EU holidays provide an exogenous shock that effectively shuts down the uncertainty resolution during EU-open. If uncertainty is not being resolved, EU-open returns should be close to zero similar to the Asian session, and instead positive returns should shift to later in the day. The data support this prediction. We obtain holiday dates from the New York Times website and manually verified them. We focus on days when the two main European exchanges, Frankfurt and London, are closed, but the US market is open and thus E-mini S&P trades all day. The list includes both recurrent holidays, such as National day in Germany or the Summer bank holiday in the UK, and special occasions, such as the Royal Wedding celebration. Of course, unique EU holidays are rare, and our sample period includes only 81 such days. Table 6 compares average returns and trading activity for holidays with the rest of the sample. E-mini futures volume and volatility drop by 54% and 19%, respectively, relative to the prior month average, which confirms the lack of uncertainty resolution during EU-open on EU holidays. Remarkably, EU-open returns are slightly *negative* on EU holidays (-0.49% p.a.), but returns are positive during the rest of the European session: 9.49% p.a., which is comparable to the average EU-open return of 7.78% on non-holidays. Perhaps uncertainty is resolved later in the day when the first US investors arrive.

The following tests explore how EU open returns depend on measures of price uncertainty. *Second*, EU-open return should be higher after high uncertainty is accumulated prior to it. The uncertainty will be high if a lot of information arrives overnight that can be measured by overnight volume and volatility. Consistent with this hypothesis, Table 7 shows that EU-open returns are higher when volatility or volume are high during the Asian session before EU-open. After controlling for Asian session, EU-open returns are not significantly related to volatility or volume of the preceding US session that US investors had a chance to process. For example, Asian volume has a *t*-statistic of 3.3 versus 1.3 for the US volume. We estimate volatility in two ways: as realized volatility from ten-second returns and as absolute return over the entire period. Volume is estimated as the number of futures contracts traded. Volume and volatility are then normalized by its two-week trailing average to account for changes in aggregate market conditions.

Third, change in VIX or its level are often used to measure uncertainty. For example, Ederington and Lee (1996) and Beber and Brandt (2006) show that uncertainty measured by option implied volatility drops after the release of macro news. Hu et al. (2019) use positive shocks to VIX to study uncertainty resolution around FOMC announcements. We find that high uncertainty, as measured by VIX or its daily change, predict higher EU-open return. The last column of Table 7 shows that VIX level is the only significant macro predictor of EU-open return (*t*-statistic of 2.2). If both VIX level and change are included, VIX change is highly significant with *t*-statistic of 4.1 and VIX level loses significance (*t*-statistic of 1.2), which is consistent with investors mainly reacting to changes in uncertainty.

Fourth, we explore four other popular daily uncertainty measures. Nick Bloom and his collaborators developed several popular text-based uncertainty measures. The daily news-based economic policy uncertainty index by Baker et al. (2016) is based on archives of thousands of newspapers from Access World News. The index counts the frequency of articles in US newspapers that contain uncertainty keywords about the economy and government. Twitter-based economic and market uncertainty indices by Baker et al. (2020) are based on all tweets sent on Twitter since January, 2010 that contain keywords related to uncertainty, the economy, or equity markets.[12] Finally, VSTOXX implied volatility on EURO STOXX 50 index, Europe's leading blue-chip index, captures European uncertainty better than VIX. Table 8 shows that EU-open

[12] A detailed description of these indices can be found at https://www.policyuncertainty.com/us_monthly.html and https://www.policyuncertainty.com/twitter_uncert.html

returns are higher after uncertainty increases as reflected by these four indices or their daily changes. In univariate regressions, all eight specifications have a positive coefficient, and seven out of eight specifications are statistically significant, the only exception is VSTOXX level (*t*-statistics of 1.4).

Fifth, how does uncertainty change around the clock? VIX is computed from prices of S&P 500 index options that do not trade during EU-open. Luckily, VIX futures actively trade overnight. They were introduced by CBOE Futures Exchange (CFE) in 2004 but became popular only after the financial crisis. On June 22, 2014, CFE finally extended VIX futures trading hours to match E-mini futures including the Asian session and EU-open. We use this sample with overnight VIX futures trading and apply the same methodology as for E-mini S&P futures. About one billion dollars of VIX futures exposure is traded during a typical overnight period.

Around the clock patterns in VIX futures returns support the uncertainty resolution hypothesis and are reported in Figure 7 and Table 9. Whaley (2013), among many others, reports highly *negative* daily VIX futures consistent with the variance risk premium. Remarkably, we find that VIX returns are *positive* during the Asian session before EU-open with an annualized cumulative return of 39.6% and a *t*-statistic of 2.8. Cumulative return steadily increases except for a temporary drop during China/Hong Kong open at 8:00 pm ET, which is consistent with uncertainty being partially resolved by Asian open. Uncertainty increases during the Asian session. Cumulative returns peak around the start of EU-open, which indirectly validates how we define this interval. VIX return during EU-open is -46.2% p.a. with a *t*-statistic of -5.2. Uncertainty decreases during EU-open and especially its second part, when European markets officially open. During EU-open, uncertainty decreases, while market returns are positive – a prediction of the uncertainty resolution hypothesis. VIX return varies wildly and is mildly negative during the rest of the day, but it is not statistically significant except for a short period around US close. Panel B of Figure 7 confirms these results; out of all four-hour windows, (1) VIX returns are positive only for the period before EU-open, (2) only during EU-Open, VIX returns are negative and significant at the 1% level, (3) returns during the rest of the day are negative but rarely statistically significant. Figure IA.6 confirms that these results hold through the entire sample period by showing a two-year moving average for VIX return and its *t*-statistic. EU-open VIX returns are negative and significant at 1% level in every two-year period.

Sixth, we show how returns respond to changes in the speed at which uncertainty is being resolved. Table IA.4 shows that uncertainty is being resolved faster during the second half of EU-open. Indeed, VIX futures returns are more negative in the second part: -41.7% versus -4.6% p.a. in the first part. The theory predicts that market returns should also be more positive in the second part, which is true: 5.9% versus 1.7%. Intuitively, as uncertainty resolution accelerates, we should also observe higher trading volume and volatility. Indeed, volatility increases from 0.11 in the first half to 0.15 in the second half. Similarly, volume increases from 37.7 to 132.2 thousand contracts. These changes are statistically and economically significant. Figure IA.7 confirms these results by showing minute-by-minute trajectories for cumulative returns on E-mini S&P and VIX futures, E-mini volume and realized volatility around EU-open.

The last two tests indirectly support the uncertainty resolution hypothesis. The last panel in Figure 2 shows that the trade size is lowest during Asian hours but starts to increase at the start of EU-open and increases by 43% during EU-open. Perhaps Asian investors trade in smaller size and European investors indeed return to the market during EU-open.

Finally, we apply a classic variance ratio test to assess price efficiency (Amihud and Mendelson, 1987). It shows that prices are least efficient during Asian hours as the variance ratio is higher pre-EU-open than post-EU-open. Variance at time t is computed as an average of squared 24-hour returns from t to $t+24h$ over all days. Figure 8 shows a ratio of variance at time t to overall daily average variance for all starting times. The variance ratio at the start of EU-open is 1.08, or 8% higher than average, and it drops to 0.95 by the end of EU-open. Thus, as measured by the variance ratio, price efficiency improved by about 14% during EU-open.

Overall, these comprehensive tests – especially EU holidays and VIX futures returns – support the uncertainty resolution explanation.

4.3 Limits to arbitrage – trading strategy

Limits to arbitrage may prevent investors from taking advantage of market anomalies. Are EU-open returns just some non-tradeable artifact of illiquidity? In this section, we explore the after-cost profitability of a trading strategy that exploits EU-open anomaly and buys E-mini futures before EU-open and closes the position at its end. We show that this strategy (1) is highly profitable after accounting for conservative estimates of trading costs, (2) has enough capacity to earn $50 million per year, (3) can be greatly improved by only trading on days with high uncertainty prior to EU-open, and (4) this timing strategy has a much higher out-of-sample R^2 than comparable strategies that predict market return.

We estimate costs conservatively by taking a perspective of a small impatient investor who pays (1) the exchange fees and commissions and (2) the entire bid-ask spread by buying at the ask and selling at the bid. The spread is almost always one tick, or \$12.5 per contract, with large depth at the best bid and ask.[13] Our estimates of costs are conservative because, in practice, investors can provide liquidity with limit orders, which are filled quickly with 121 trades per minute during Asian hours. Practitioners rely on execution algorithms that optimally provide and take liquidity, and the average execution price is only slightly worse than the pre-trade midquote (e.g., Anand, Irvine, Puckett, and Venkataraman, 2012). We assume that fees and commissions are \$2.50 per roundtrip (/rt) per contract, or 1/5 of the tick. Broker commissions are small relative to CME fees. The CME exchange fees for trading E-mini at Globex for non-members increased to \$2.36/rt by 2018. Our fee estimates are conservative because active investors can reduce exchange fees and commissions to less than \$1.0/rt by owning or leasing a CME member seat.[14] Also, the trading strategy is easy to automate as E-mini futures are traded electronically.

Panel A of Table 10 reports returns of the baseline strategy with and without trading costs. Before costs, the strategy makes a 7.76% annualized return with a Sharpe ratio of 1.65. After costs, the profitability is expectedly lower; average return declines to 2.6% with Sharpe ratio of 0.55. The return remains statistically significant, and the after-cost Sharpe ratio is higher than 0.36 for a buy-and-hold strategy that holds a long position for the entire day with no costs.

The baseline strategy assumes conservative costs and sets an upper bound for the after-cost profits. It can be substantially improved. Instead of trading every day, one can trade only on days when expected returns are higher than average. To implement this conditional strategy, we estimate a linear model that predicts EU-open returns out-of-sample. The model only relies on two ex-ante predictors: (1) daily change in VIX (from 4:15 pm to 4:15 pm), and (2) realized volatility during Asian hours before EU-open (from 6:00 pm to 11:30 pm). Both predictors are motivated

[13] We estimate bid and ask prices from trades, which is relatively straightforward as the bid-ask spread is almost always one tick, and hundreds of trades are executed at bid and ask every minute. We confirm that bid and ask prices implied from trades almost always match actual bid and ask prices for the sample period with available quote data, and the profitability for strategies computed on trades versus quotes is very similar. We prefer the trade-based bid and ask prices because they rely on actual trades and are available for a longer period.

[14] Small hedge funds who specialize in E-mini futures often prefer to lease a CME IOM seat for about \$300/month that lowers exchange fees to \$0.55/rt after a volume discount. A one-time membership application fee is \$2000.

by the uncertainty resolution hypothesis: price discount is larger when uncertainty is high leading to higher EU-open return. Indeed, EU-open return is higher when VIX and the Asian volatility increase. To focus on out-of-sample, we first estimate the model on the first year of data (2004) and use the estimated coefficients to forecast EU-open returns daily for the next month (1/2005). We then repeat the steps: expand the estimation window by one month, re-estimate the model, and apply it to next month.

This simple predictive model works remarkably well. The out-of-sample R^2, is 6.57% and is stable over the sample period (Figure IA.10).[15] The out-of-sample R^2 is only slightly smaller than an in-sample R^2 of 7.49%. To put this number in perspective, Gao et al. (2018) predict intraday returns for SPY ETF and find an R^2 of 2.6%, that they characterize as “a level that exceeds typical predictive R^2 s at the monthly frequency.” After the predictive model is estimated, we compute out-of-sample forecasts for EU-open returns, trade only on the days when the ex-ante conditional forecast exceeds 1.5 times total transactions costs, and weigh all days equally. It makes sense to trade only on days when expected profits exceed costs. The conditional strategy trades on 40.2% of days, or 2 out of 5, and Figure IA.10 shows that trading frequency is relatively stable over time. The conditional strategy can be further improved by reducing trading costs or sizing trades proportional to forecasted returns.

Table 10 shows that the conditional strategy is almost as profitable as the baseline that trades every day. Its cumulative return is 6.76% per year before costs compared to 7.76% for the baseline, despite trading on only 40% of days. Thus, EU-open returns are low on no-trade days, 1.07% p.a. Per-trade costs do not change, as the bid-ask spread is almost always one tick. But the cumulative costs are lower as the strategy only trades on a few days. Alternatively, the conditional strategy picks days with more than double average return, while trading costs are similar across days. After-cost expected return is 4.61% with a *t*-statistic of 4.6. Its Sharpe ratio is 1.20, in the same range as the pre-cost Sharpe ratio for the baseline strategy (1.65). Figure IA.9 shows cumulative returns for baseline and conditional strategies over time. Overall, the conditional strategy is highly profitable after costs and is more practical than the baseline strategy. The conditional strategy also validates the uncertainty resolution hypothesis by showing out-of-sample that EU-open returns are much higher after uncertainty increases prior to EU-open.

[15] We compute the out-of-sample R^2 following Campbell and Thompson (2008). Intuitively, R^2_{OS} measures how much better the predictive model performs than the forecast based on the historical average.

How much capital can these strategies accommodate? How well do average returns translate into dollar profits? Acquiring large positions causes price impact that is hard to estimate from the public data on individual trades. Nevertheless, even these data can provide useful insights subject to simplifying assumptions. Practitioners estimate that commercial execution algorithms can trade up to 10% of the average total volume without price impact.[16] We rely on this number to estimate a strategy's capacity and assume that a strategy can buy 10% of observed trading volume during each minute at the ask price. The estimated capacity is approximately linear in this parameter. The position is accumulated over a four-hour window: from two hours prior to EU-open at 9:30 pm to 1:30 am, two hours into EU-open. EU-open returns are particularly positive during the second half justifying buying into EU-open. As in a standard VWAP algorithm, we assume that futures are always bought at the ask minute-by-minute executing 10% of recorded trading volume. Similarly, the position is closed by selling futures minute-by-minute at the bid, executing 10% of volume starting at the end of EU-open (3:30 am). The position can be usually closed within an hour due to higher volume during the European session. Subject to these simplifying assumptions, we evaluate trade capacity for the baseline and conditional strategies before and after costs. In practice, risk-managers enforce limits on traders' positions. Thus, we consider two variations of the strategy: (1) unconstrained, and (2) constrained. The constrained strategy puts a cap on the maximum position size on days with extremely high volume, such as US Election night (11/09/2016) or the night after "Volmageddon" (02/06/2018).[17] EU-open strategies take large positions and make high dollar profits on these days. We prefer a more conservative constrained strategy that limits profits on those influential days.

Panels B of Table 10 reports results for unconstrained and constrained strategy variations. We highlight the more conservative constrained strategy. The conditional strategy often trades on high volatility and volume days, and thus it typically acquires a larger position: \$9.3 billion of S&P 500 exposure versus \$6.9 billion for the baseline strategy. Investors can deploy significant capital into these strategies. The EU-open strategy has no analogs in academic literature, but its capacity can be compared to short-term reversal strategy in US equities that has a break-even capacity of \$9 billion, according to Frazzini, Israel, and Moskowitz (2012). The EU-open strategies

[16] For example, ITG (2015), MSCI (2019) "Liquidity Metrics" report, and Capponi, Menkveld, and Zhang (2019).
[17] The cap is set to the lesser of 10% of recorded trading volume (as in the unconstrained strategy) or 30% of the median volume during the accumulation window over the trailing two months. Thus, for very active sessions with a lot of liquidity, the position is approximately three times as large as for regular days.

earn large after-cost profits. The baseline strategy earns before and after-cost profits of $80 and $40 million per year, while the conditional strategy earns $60 and $50 million pre- and post-costs. The unconstrained version of the strategy earns three times higher annual profits. These estimates provide a starting point for evaluating EU-open tradability.

Finally, even long-term investors can benefit from high EU-open returns. They can reduce trading costs by timing trades. If a long-term investor wants to buy (sell), the best time is before (after) EU-open; investors benefit from high EU-open return as they are not compensated for holding market risk during the rest of the day.

4.4 Data mining

Can pure luck explain positive EU-open returns and zero returns during the rest of the night? Perhaps the "true" expected return for EU-open is not as high, and another period is responsible for positive overnight returns. First, average realized returns can differ from expected returns. Maybe EU-open (rest-of-night) returns have been unexpectedly high (low). Second, we focus on a four-hour period with the highest return. Statistically speaking, in a regression of realized returns on four-hour indicators, EU-open can have the highest significance just by chance. This is a classic multiple testing problem: we must adjust *p*-values to account for taking the maximum over all four-hour periods. Fortunately, well-developed statistical tests help address this concern: from the Bonferroni adjustment to the White (2000) bootstrap reality check.

Results so far repeatedly confirm how robust and consistently positive EU-open returns are. Several of them are particularly useful for addressing the data mining concerns. EU-open return is positive in every one of fifteen years in our sample (Table 4). Even the lowest annual return is as high as 2.25% with *t*-statistics of 1.6 in 2017. To put this in perspective, the probability of 15 heads in a row while flipping a coin is 0.003%. If we compare the first and second parts of the sample, minute-by-minute trajectories for cumulative E-mini returns for the after-hours session including EU-open are very similar (Figure 10). The results are not specific to S&P 500 index and are almost identical for E-mini futures on Nasdaq and Dow indices (Figure IA.2). VIX futures returns in Section 4.2 provide another out-of-sample test.

We conduct two tests for multiple hypotheses that evaluate how picking the best performing period affects our results. The Bonferroni correction is the oldest and most conservative such test. It assumes that an econometrician picks a maximum over multiple independent hypotheses. Thus, a *p*-value must be multiplied by the number of hypotheses. For example, if the regular p-value is 1% with ten hypotheses, then the adjusted p-value is 10%. Average EU-open return has a t-statistic of 6.35, a p-value of 10^{-10}. Even if we consider all four-hour windows with a half-hour step, the adjusted p-value is 2×24 times higher and still well below the 1% significance level (5×10^{-8}). The Bonferroni correction is conservative because these four-hour periods overlap and are not independent. The main result also easily passes less conservative (than the Bonferroni) tests such as Romano and Wolf (2005) or Hansen, Lunde, and Nason (2011).

White's (2000) reality check also confirms that the high Sharpe ratio during EU-open cannot be explained by selecting the best one- or four-hour period. This popular test uses bootstrap to preserve dependencies in the data. First, returns are demeaned by subtracting average return for each minute across all days because average returns are zero under the null hypothesis. Second, we bootstrap a return sample of the same size as the original sample by sampling trading days with replacement to preserve the intraday correlations as in block bootstrap. We identify a four (one) hour period with highest t-statistic (or the Sharpe ratio) in the bootstrapped sample and record its t-statistic. After repeating this step 10,000 times, we construct a bootstrapped distribution of maximum t-statistic under the null hypothesis of zero expected return. A 99% percentile of this t-statistic distribution equals 4.0 (3.7) for one-hour (four-hour) horizons, much higher than a conventional threshold of 2.57. With its t-statistic of 6.35, EU-open easily passes White's reality check. Although not directly related, the 4.0 threshold is more conservative than the t-statistic level that the literature on false discoveries suggests for evaluating equity cross-sectional anomalies (e.g., Harvey, Liu, and Zhu, 2016).

4.5 Inventory risk

What if some investors are averse to the overnight period because of lower liquidity or fear that the market moves while they are away? To avoid this period, investors can hedge or not carry positions overnight as many day-traders and high-frequency traders do. If so, such investors have to pay a premium to liquidity providers, who take this risk. Inventory risk arises because liquidity providers are risk-averse and have limited capital. They are required to accommodate customer order flow and thus hold suboptimal portfolios. Dealers must be compensated for holding this risk, which increases in undesired position size, asset volatility, dealer's risk aversion, and expected holding period (one night in our case).[18] If investors agree that the overnight period is undesirable,

[18] This idea goes back to at least Stoll (1978). For example, Bessembinder (1992) shows that returns for some futures vary with the net holdings of hedgers, after controlling for systematic risk.

overnight returns will be positive even without trading because equities are in positive net supply – whoever caries positions overnight is compensated.[19] According to this channel, returns should be positive during the entire overnight period including EU-open, which is rejected by the data.

EU-open returns can also be positive if price pressure at the open is unexpected. This let us highlight that the average return should not be confused with price reversal, a distinct economic phenomenon. If investors buy at the close (and thus dealers are short), their price pressure causes positive returns that subsequently reverse overnight as dealers are compensated for carrying inventory that they gradually liquidate. EU-open return is negative as part of this price reversal. The price increase at the close must match the price reversal overnight on average, for a zero net return. If the two price impacts do not match, prices can be manipulated by faking price pressure. Alternatively, if investors sell at the close, closing return will be negative followed by positive overnight reversal, including EU-open. Thus, inventory risk implies a price reversal after an inventory shock at the close. If investors regularly buy a large position during EU-open, prices will increase in anticipation during Asian hours. Assuming dealers' expectations are rational, only unexpected shocks to inventory matter. If so, buying and selling surprises are equally likely, positive and negative reversals cancel out for a zero average return. According to this channel, average EU-open returns should be zero despite strong overnight price reversal. We focus on explaining the average market returns, while Boyarchenko et al. (2020) complement our results by focusing on the overnight reversal. In small samples, realized imbalances may differ from dealer's expectations, and unusually high order imbalance during EU-open could produce positive average returns. Of course, dealers should be able to properly estimate the imbalances with 15 years of daily data and consistently positive EU-open returns. If prices rebound so strongly around EU-open, then an equally large price drop should be around European or US close, but if anything, returns are positive around US close as Figures 1, 3 and 4 show.

Inventory risk seems intuitive and plausible. But on a closer look, this hypothesis faces numerous challenges in explaining *average* EU-open returns. Its predictions, which we evaluate one-by-one, do not line up with the data.

[19] It is not entirely clear why investors are so scared of the overnight period and specifically the Asian session. This session is less risky than Europe and US as measured by variance. Leaving for a long lunch in the middle of the US session is almost as risky as the entire Asian session. The Asian period before EU-open contributes 10% to the variance, EU-open contributes another 8%, while 6.75 hours of the US trading session contribute 60%. Figure IA.4 compares cumulative return in calendar and variance times.

The main challenge for inventory models is why dealers are compensated only during EU-open but not the rest of the night. To compensate dealers, overnight return must be positive through the entire night, but dealers lose money as cumulative return is slightly negative in the pre-EU-open period, -1.25% p.a., with a Sharpe ratio of -0.25 in Table IA.1. Figure 1 shows that returns are zero or slightly negative through the entire Asian session. An opportunistic investor, who carries no inventory risk and thus deserves no compensation, can earn the same EU-open return as the dealers by "cutting the line" and buying right before EU-open. Section 4.3 shows that this strategy is profitable after costs. The free rider can boost returns by buying at the bid as s/he loses nothing if the limit order is not executed. Thus, negative pre-EU-open returns combined with large positive EU-open returns are hard to reconcile with the inventory risk hypothesis but are consistent with the uncertainty resolution hypothesis.

Perhaps inventory risk is priced because the Asian session is highly illiquid, and investors have to wait until European open to adjust their positions. But waiting until EU-open is a waste of time. With an average volume of 2.4 billion dollars per hour (pre-EU-open), the Asian session is certainly liquid enough to accommodate large trades. Waiting until EU-open does not reduce trading costs for small trades as the bid-ask spread is almost always one tick with $5.6 million available for immediate execution at best bid or ask. E-mini trading is fully electronic, and trade execution can be automated either in-house or with broker-supplied algorithms.

We directly test whether the inability to trade during Asian hours or its perceived illiquidity affect overnight returns. First, while investors can trade continuously during a regular overnight session, the E-mini market is closed for most of the weekend from 4:15 pm on Friday to 6:00 pm on Sunday. Thus, the premium for inventory risk should be larger over weekends than on weekday nights. Figure 9 compares cumulative return and trading volume over a day on weekdays versus weekends. Weekend returns are noisier because they are four times less frequent than weekdays. But if anything, EU-open returns are lower on weekends than on other days, 4.8% versus 8.2%. Thus, non-trading periods do not carry a higher premium in our sample.

Next, we test whether night illiquidity leads to higher premium for inventory risk by comparing the earlier and later parts of the sample (pre and post 2011). Luckily, liquidity during the Asian session increased substantially. Figure 10 shows that while trading volume remained unchanged during the US session, it doubled for the European session and quadrupled for the Asian session. Overnight liquidity improved substantially, but the trajectories for cumulative returns during the first and second parts are very similar throughout the entire overnight session, including EU-open. Returns diverge only during the US session due to the financial crisis in the pre-2011 period. Overnight liquidity does not affect EU-open return, but it should according to the inventory risk hypothesis. We also evaluate the effect of the increased liquidity on EU-open returns with two univariate regressions. We compute the annual average return for pre-EU-open and EU-open periods and regress them onto the average annual volume share of the Asian session as percentage of total volume. Table IA.5 shows that as liquidity during the Asian session increases, the return for pre-EU-open decreases slightly (*t*-statistic of -2.18), while the return for EU-open does not change (*t*-statistic of 0.24). Inventory risk hypothesis predicts that as Asia becomes much more liquid, EU-open returns should decrease and perhaps move to the Asian session as dealers prefer to offload their positions sooner. Both predictions are not supported by the data.

We also study inventory shocks directly. If dealers receive no inventory shock at the US close, as measured by order imbalance, then high EU-open returns should disappear without price pressure at the close. But EU-open returns remain large for the subsample with zero order imbalance. Following Easley, Lopez de Prado, and O'Hara (2016), we estimate order imbalance with block volume classification approach using 10-second bars and tick rule. We rank days by their order imbalance during the last hour of the US session (from 3:15 pm to 4:15 pm) and compute next-day EU-open return for two samples with low order imbalance: the wider one for order imbalance between 25% and 75% percentiles and the narrower one for order imbalance between 40% and 60%. Panel A of Table 11 confirms that order imbalance is only 0.4% for both samples. EU-open returns are large: 6.70% and 8.44% for the 25-75 and 40-60 samples. Both returns are significant and are not statistically different from the full sample average (7.6%). Pre-EU-open returns are slightly negative. Figure IA.8 shows cumulative returns over the day for the 40-60 sample are similar to the full-sample returns in Figure 1. Returns are slightly negative overnight, but the trend reverses exactly at the start of EU-open, with positive return trend during EU-open, and then returns become flat for the rest of the European session. Although order imbalance might explain return reversal, it does not affect average EU-open returns.

Finally, we show that in a direct horse race, inventory risk is subsumed by uncertainty resolution. This test takes seriously the idea that order imbalance at the US close predicts return reversal at EU-open. We compute order imbalance and VIX change – common proxies for inventory risk and uncertainty resolution – during the last hour of the US session. Panel B of Table

11 shows that both variables predict EU-open return in univariate regressions, but order imbalance has a lower R^2, 1.9% versus 7.2%. But in a joint regression, the coefficient for order imbalance becomes virtually zero with a *t*-statistic of -0.3, while VIX change remains significant with a *t*-statistic of 3.1. Thus, the return predictability is driven by change in uncertainty. Results remain the same if we control for macro variables and sentiment measures. Overall, uncertainty resolution rather than inventory risk explains return reversal at EU-open.

4.6 Other explanations

We consider other explanations. Conventional risk-based theories attribute expected returns to higher risk as reflected by market volatility, negative price jumps, and negative skewness, among other measures. But EU-open is less compared to the rest of the day according to these measures. The peso problem cannot explain why EU-open returns are positive in every year and differ so much from returns in adjacent intraday periods. Perhaps close-to-open stock returns are positive because most news arrives at night. Indeed, market-moving US news such as earnings announcements and many macro news are released shortly before US open or after US close. But EU-open occurs while US is in deep night, which is at least five hours away from these news intensive periods. Even most European macro news are announced after EU-open's end.

An investor sentiment hypothesis argues that European investors are buying at the open because they are more optimistic than everyone else. We test this hypothesis by studying how EU-open return depends on measures of investor sentiment including the bull-bear sentiment from the AAII investor survey (proxy for the sentiment of US retail investor), Baker and Wurgler (2006) index (proxy for institutional investor sentiment), the University of Michigan consumer confidence, and the TED spread. None of them significantly predict EU-open returns in Table 7 except for Michigan consumer sentiment that is significant at the 10% level in some specifications.

Carry costs – interest/margin payments and security lending fees – are typically incurred after regular trading hours. Perhaps market return should be higher overnight to compensate investors for the costs. It is not clear whether any of these costs are concentrated in EU-open. Carry costs are usually proportional to interest rates, but last column of Table 7 shows that EU-open returns do not depend on interest rates. Also, most carry costs are incurred every calendar day and thus are higher over weekends, but EU-open returns are slightly lower over weekends, although the difference is not statistically significant (Figure 9 and Panel A of Table 5).

Algorithmic trading and high-frequency trading (HFT) have been extensively adopted during our sample period and could be responsible for some of the return patterns. Although we do not observe which trades are initiated by algorithms, average EU-open returns changed little during the sample period and thus unlikely to be impacted by the growth of HFT.

5. Conclusion

In this paper, we introduce and explain a new puzzle about average excess market return. We use prices of E-mini S&P futures that are actively traded almost 24/5 to study how excess return for S&P 500 index depend on the time of day. One period clearly stands out: 100% of the average market return is concentrated in four hours between 11:30 pm and 3:30 am ET, which is deep night in US and early morning in Europe. Return is particularly high when European markets open in the second half of this period. In contrast, average return is close to zero during any other four-hour period. EU-open has low volatility leading to an impressive Sharpe ratio. The EU-open return pattern is very consistent and is observed in every year, calendar month, and weekday. We also show that a strategy of buying/selling futures before/after EU-open is profitable net of conservative estimates of trading costs and has a large capacity.

Using daylight savings time as an exogenous shock to relative time between Europe and Asia, we show that EU-open return is driven by the European open rather than the Asian close. We consider several potential explanations. One of them, uncertainty resolution, is particularly promising. Normally, investors quickly process arriving information and keep prices close to the fundamental value. But during the Asian session, most investors sleep and thus do not participate in information processing. As a result, uncertainty accumulates through Asian hours, and price can further deviate from value. As European investors wake up and process the accumulated information, uncertainty is resolved, and price increases during EU-open. Several tests, most notably EU-open returns on EU holidays and VIX future returns around the clock, support this theory. Zero market returns during the rest of the day are harder to explain.

Taken at face value, these results have several implications. First, price uncertainty arises naturally in financial markets, and its resolution is a critical determinant of the average market return. Second, US investors receive most attention; and European investors are usually neglected, but they help resolve uncertainty during EU-open. Finally, average market return has an "atomistic" structure in the data: positive during EU-open and some macro news such as FOMC announcements, but zero during the rest of the time. In contrast, conventional theories imply "continuously" positive returns. Hopefully, future research can reconcile these two observations.

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Table 1
Returns during EU-open and the rest of the day

This table reports main statistics for E-mini S&P futures returns, including return average, *t*-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. All these measures are computed from annualized log returns (period return times 252) and, when applicable, are reported as percent. E.g., the average return during EU-open is 7.60% annualized. Also reported are return distribution percentiles, which are not annualized. E.g., the minimum return during EU-open is -3.95% per day. The entire trading day in the last column is split into EU-open (from 11:30 pm to 3:30 am ET) and the rest of the day (6:00 pm to 11:30 pm and 3:30 am to 6:00 pm). *t*-statistic is computed to account for heteroskedasticity and autocorrelation. Max drawdown is the difference between a portfolio's point of maximum return and any subsequent low point of performance only using the same subperiod, such as EU-open.

	EU-open	Rest of the day	Entire day
Average return, % p.a.	7.60	-0.80	6.80
t-statistic	6.35	-0.17	1.39
Standard deviation, % p.a.	4.55	17.79	18.63
Sharpe ratio, p.a.	1.67	-0.05	0.36
Skewness	1.64	-0.99	-0.42
Kurtosis	56.96	15.77	16.80
Min, %	-3.95	-13.07	-12.01
5%	-0.32	-1.77	-1.73
25%	-0.08	-0.41	-0.39
50%	0.02	0.06	0.08
75%	0.13	0.52	0.54
95%	0.41	1.47	1.57
Max, %	4.52	8.47	11.28
Max drawdown, %	7.96	66.40	61.89

Table 2
Trading hours for major equity markets
This table reports trading hours and lunch break time, if applicable, for major equity markets. Hours are reported in local time zone and Eastern Time. Daylight Savings Time (DST) in Europe extends from the last Sunday in March to the last Sunday in October; DST in US extends from the second Sunday in March to the first Sunday in in November. Additional exchanges that open at 2:00 ET: Moscow, Johannesburg, Tel-Aviv, Saudi, Bursa Istanbul; at 3:00 ET: Euronext (Amsterdam, Brussels, Lisbon, London), Swiss, Spanish, Milan, Stockholm: and at 9:30 ET: Toronto, Mexico.

Stock Exchange	RTH (Local Time)	RTH (EST)	Lunch (EST)	DST
Japan	9:00–15:00	19:00–1:00	21:30-22:30	None
Shaghai, Shenzhen	9:30–15:00	20:30–2:00	22:30-23:30	None
Hong Kong	9:30–16:00	20:30–3:00	23:00-0:00	None
Frankfurt	8:00–20:00	2:00–14:00	None	Mar–Oct
Eurex	8:00–22:00	2:00–16:00	None	Mar–Oct
London	8:00–16:30	3:00–11:30	None	Mar–Oct
Euronext (Paris)	9:00–17:30	3:00–11:30	None	Mar–Oct
NYSE, NASDAQ	9:30–16:00	9:30–16:00	None	Mar–Nov

Table 3
Trading activity during a trading day

This table reports averages for several trading activity and liquidity measures for E-mini S&P 500 futures for selected intraday intervals. The entire trading day (last column) represents the daily continuous session (6:00 pm to 4:15 pm) and is split into Asia pre EU-open (6:00 to 11:30 pm), EU-open (11:30 pm to 3:30 am), Asia (6:00 pm to 2:00 am), Europe (2:00 am to 9:30 am), US (9:30 am to 4:15pm). The measures include trading volume, number of trades, trade size, the bid-ask spread, and the market depth. Measures are reported per minute and as period totals. The bid-ask spread is almost always one tick ($12.50). The relative bid-ask spread is the difference between bid and ask prices normalized by the quote midpoint and is reported in basis points. Market Depth = 0.5 × (Best Bid Size + Best Ask Size). The statistics for the bid-ask spread and market depth are based on the subsample with available quote data from 2006 to July 2018. S&P 500 index average is 1634 during this subperiod and is 1566 during the full sample from 2004 to July 2018.

	EU-open	Asia pre EU-open	Asia	Europe	US	Entire day
Length, hours	4	5.5	8	7.5	6.75	22.25
Volatility, annualized	0.16	0.15	0.14	0.20	0.32	0.23
Volume, per minute, contracts	708	475	429	2341	20128	7050
Volume, per minute, $M	58	40	36	183	1535	540
Volume, total, $B	14	13	17	82	622	721
Number of trades, per minute	195	131	121	547	3159	1186
Number of trades, total, 000s	47	43	58	246	1279	1584
Average trade size, contracts	3.7	3.5	3.4	4.9	8.0	5.3
Bid-ask spread, ticks	1.034	1.035	1.036	1.021	1.005	1.022
Bid-ask spread, b.p.	1.71	1.71	1.71	1.71	1.69	1.70
Market depth, contracts	73.7	65.6	64.6	133.5	442.4	202.4
Market depth, $M	6.2	5.6	5.5	10.8	34.3	16.0

Table 4
Returns by year

This table reports main statistics for E-mini S&P futures returns by year. The statistics include average return, standard deviation, and *t*-statistics. All these statistics are based on annualized log returns (period return times 252) and, when applicable, are reported as percent. E.g., the average return during EU-open in 2004 is 4.53% annualized. The entire trading day is split into EU-open (from 11:30 pm to 3:30 am ET) and the rest of the day (6:00 pm to 11:30 pm and 3:30 am to 6:00 pm). *t*-statistics is computed to account for heteroskedasticity and autocorrelation. Last row reports sample average.

	EU-open			Rest of the day		
	Average return, %	Std. dev., %	*t*-stat.	Average return, %	Std. dev., %	*t*-stat.
2004	4.53	2.20	2.06	4.53	11.05	0.41
2005	7.12	1.86	3.83	-5.77	10.40	-0.56
2006	5.71	2.05	2.78	4.81	9.95	0.48
2007	6.96	2.96	2.34	-8.63	15.66	-0.55
2008	9.80	10.41	0.94	-55.82	39.25	-1.42
2009	16.24	5.81	2.79	4.19	24.89	0.17
2010	5.60	4.70	1.19	8.37	18.43	0.45
2011	8.85	6.76	1.31	-5.52	23.36	-0.24
2012	6.40	3.08	2.06	9.09	14.35	0.63
2013	6.06	2.66	2.27	18.36	10.85	1.69
2014	5.66	2.21	2.55	7.54	11.05	0.68
2015	13.52	3.38	4.00	-12.89	15.05	-0.86
2016	5.38	4.33	1.24	5.71	12.43	0.46
2017	2.25	1.38	1.63	15.83	6.29	2.51
2018	11.47	5.64	1.55	-2.50	14.97	-0.13
Total	7.60	4.55	6.35	-0.80	17.79	-0.17

Table 5
Returns by weekday and calendar month

This table reports main statistics for E-mini S&P futures returns by day of week (Panel A) and by calendar month (Panel B), including average return, *t*-statistics, standard deviation, and Sharpe ratio. They are based on annualized log returns (period return times 252) and, when applicable, are reported as percent. E.g., the average EU-open return on Monday (over the weekend) is 4.83% annualized. The entire trading day is split into EU-open (from 11:30 pm to 3:30 am ET) and the rest of the day (6:00 pm to 11:30 pm and 3:30 am to 6:00 pm). *t*-statistic is computed to account for heteroskedasticity and autocorrelation. Last row reports sample average.

Panel A

	EU-open				Rest of the day			
	Average return, %	Std. dev., %	Sharpe ratio	*t*-stat.	Average return, %	Std. dev., %	Sharpe ratio	*t*-stat.
Monday	4.83	4.87	0.99	1.63	-4.68	18.62	-0.25	-0.41
Tuesday	9.64	5.77	1.67	2.79	10.29	17.07	0.60	1.04
Wednesday	8.72	3.97	2.20	3.83	-0.68	18.68	-0.04	-0.06
Thursday	8.51	3.91	2.17	3.71	-0.33	17.95	-0.02	-0.03
Friday	6.02	3.97	1.52	2.61	-9.16	16.59	-0.55	-0.94

Panel B

	EU-open				Rest of the day			
	Average return	Std. dev.	Sharpe ratio	*t*-stat.	Average Return	Std. dev.	Sharpe ratio	*t*-stat.
January	3.11	4.06	0.77	0.83	-17.72	17.19	-1.03	-1.12
February	11.49	4.96	2.32	2.48	-5.63	16.43	-0.34	-0.37
March	10.59	3.39	3.13	3.57	5.86	17.03	0.34	0.39
April	7.06	3.14	2.25	2.49	12.60	14.07	0.90	0.99
May	4.86	3.67	1.33	1.49	-0.12	14.34	-0.01	-0.01
June	9.53	3.38	2.82	3.18	-19.72	15.50	-1.27	-1.44
July	5.71	3.26	1.76	1.96	14.31	14.01	1.02	1.14
August	8.26	5.56	1.49	1.65	-14.18	17.97	-0.79	-0.87
September	7.87	4.08	1.93	2.06	-4.78	19.06	-0.25	-0.27
October	3.75	8.28	0.45	0.50	3.90	24.90	0.16	0.17
November	7.11	5.00	1.42	1.52	7.25	22.34	0.32	0.35
December	11.96	3.40	3.52	3.78	8.52	18.04	0.47	0.51

Table 6

EU-open returns on European holidays

This table compares average EU-open returns, volatility, and trading volume on EU holidays with the rest of the sample. We report statistics for EU-open and the rest of the European session ("after EU-open"). Normalized volume and volatility are computed relative to their prior monthly average. Unique EU holidays include days when London or Frankfurt stock exchanges are closed but US stock market is open, 81 events in total. The last two columns report the difference between the two samples and its *t*-statistic, which is adjusted for autocorrelation and heterogeneity.

	EU Holidays	Rest of sample	Difference	*t*-stat. for difference	Relative change
Return, EU-open, %	-0.49	7.78	-8.27	[-2.2]	
Return, after EU-open, %	9.49	-0.37	9.87	[1.5]	
Log volume, EU	12.589	13.474	-0.885	[-10.1]	-6.6%
Log volume, EU, norm.	0.468	1.021	-0.553	[-21.0]	-54.1%
Volatility, EU	2.507	3.477	-0.971	[-9.3]	-27.9%
Volatility, EU, norm.	0.807	0.992	-0.185	[-11.7]	-18.7%
|Return|, EU	0.410	0.723	-0.312	[-6.8]	-43.2%
Num. Obs.	81	3,574			

Table 7
Conditional EU-open returns

This table shows how market returns during EU-open depend on lagged market conditions. For the columns marked (1) through (4), we focus on short-term predictors based on the Asian session before EU-open and previous US session. We include VIX index (implied volatility for one-month SPX options) and its change from previous close. We also include shocks to log volume, absolute returns, and volatility during these two periods. In column (5), we show how EU-open return depends on macro variables measured at the previous close: VIX index, short-term Treasury rate, term spread (difference between long-term and short-term rates), TED spread (difference between on-month LIBOR and Treasury rates), bull-bear spread from AAII Investor Sentiment Survey (mood of US individual investors), Baker and Wurgler (2006) sentiment, University of Michigan Consumer Sentiment Index (US consumer confidence), and a weekend indicator. Standard errors are adjusted for autocorrelation and heterogeneity.

	EU-open return				EU-open return	
	(1)	(2)	(3)	(4)		(5)
VIX change	0.0970***				VIX	0.0168**
	[4.1]					[2.2]
VIX	0.0054				Treasury bill	0.0079
	[1.2]					[0.8]
Volume, Asia		0.1282***			Term spread	0.0076
		[3.3]				[0.4]
Volume, US		0.0714			TED spread	-0.1518
		[1.3]				[-1.6]
|Ret|, Asia			0.1676**		Retail invest sent.	-0.0836
			[2.6]			[-0.7]
|Ret|, US			0.0204		BW sent.	0.1534
			[1.2]			[1.2]
Volatility, Asia				0.3660***	UMich. cons sent.	0.0048*
				[3.0]		[1.8]
Volatility, US				0.2589*	Weekend	-0.0306
				[1.8]		[-0.9]
Intercept	-0.0235	-0.125**	-0.030	-0.539***	Intercept	-0.5834
	[-0.3]	[-2.0]	[-0.8]	[-2.8]		[1.6]
R^2	0.062	0.013	0.031	0.021	R^2	0.017
Num. Obs.	3653	3,645	3,654	3,645	Num. Obs.	3,654

Table 8
Uncertainty measures predict EU-open returns

This table shows how EU-open returns depend on lagged uncertainty measures. We report the coefficient and *t*-statistic of a univariate regression of EU-open return on lagged daily change in uncertainty (Column 2) or uncertainty level (Column 3). The daily uncertainty measures include VSTOXX (implied volatility on EURO STOXX 50 index), the news-based economic policy uncertainty index by Baker, Bloom and Davis (2016), and Twitter-based economic uncertainty (TEU) and market uncertainty (TEU) indices by Baker, Bloom, Davis, and Renault (2020). The last column reports the number of observations for each variable. *t*-statistic is adjusted for autocorrelation and heterogeneity.

Uncertainty measure	Change	Level	Num. Obs.
Economic policy uncertainty	0.0009**	0.0014**	3,653
	[2.0]	[2.2]	
Twitter economic uncertainty	0.0003**	0.0004**	1,900
	[2.5]	[2.2]	
Twitter market uncertainty	0.0004***	0.0007***	1,900
	[2.7]	[3.2]	
VSTOXX index	0.0650***	0.0066	3,057
	[3.0]	[1.4]	

Table 9

VIX futures returns during EU-open and other intervals

This table reports main statistics for VIX futures returns including return average, *t*-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. All these measures are computed from annualized log returns (period return times 252). E.g., average return during EU-open is -46.26% annualized. We also report return distribution percentiles, which are not annualized (e.g., minimum return during EU-open is -13.62% per day). The entire trading day (last column) is split into Asia before EU-open, EU-open, rest of the day until US close ("post-EU-open") and the period around US close. Max drawdown is the difference between a portfolio's point of maximum return and any subsequent low point of performance.

	Asia pre-EU-open 6:00 pm-11:30 pm	EU-open 11:30 pm-3:30 am	Post-EU-open 3:30 am-2:00 pm	US-close 2:00 pm-4:15 pm	Total 6:00 pm-6:00 pm
Average return, % p.a.	39.57	-46.26	-21.39	-50.83	-78.49
t-statistic	2.80	-5.20	-0.88	-2.20	-2.13
Standard deviation, %	28.63	18.04	49.53	46.90	74.85
Sharpe ratio, p.a.	1.38	-2.56	-0.43	-1.08	-1.05
Skewness	8.35	-2.07	0.61	7.67	1.73
Kurtosis	154.93	24.69	4.65	150.93	17.74
Min, %	-10.79	-13.62	-10.88	-10.89	-18.91
5%	-1.79	-2.02	-4.65	-3.93	-7.02
25%	-0.40	-0.62	-1.92	-1.39	-2.75
50%	0.00	0.00	-0.38	-0.27	-0.62
75%	0.62	0.36	1.42	0.70	1.59
95%	1.86	1.38	5.67	3.92	7.23
Max, %	35.15	5.14	13.03	58.24	48.07
Max drawdown, %	13.82	87.42	90.71	94.54	98.99

Table 10
Trading strategy

Panel A reports profitability of a trading strategy that buys E-mini futures at the start of EU-open and sells them at the end of EU-open, with and without transaction costs ("TC"). We report annualized average return, standard deviation, Sharpe ratio, and *t*-statistic. The baseline strategy trades every day, while the conditional strategy trades on about 40% of days with higher expected EU-return as predicted by an out-of-sample linear model with daily change in VIX and Asian volatility. The transaction costs include paying the full bid-ask spread and exchange fees/commissions. Panels B reports annual dollar profits (P&L) and average position on a typical day a strategy trade. The strategy accumulates positions during a four-hour window by buying 10% of trading volume at the ask minute-by-minute. The accumulation window from two hours before to two hours into EU-open (9:30 pm to 1:30 am). Similarly, the position is liquidated by selling 10% of minute-by-minute volume at the bid, which usually takes less than an hour.

Panel A. Strategy without accumulation window

Strategy	Average return, %	Std. dev., %	Sharpe ratio	*t*-stat.
Baseline, no TC, %	7.76	4.72	1.65	6.27
Baseline, with TC, %	2.58	4.71	0.55	2.09
Conditional, no TC, %	6.69	3.86	1.73	6.60
Conditional, with TC, %	4.61	3.84	1.20	4.57

Panel B. Trading capacity and profits for strategy with accumulation window

	No constraints		Position constraints	
Strategy	P&L, $M p.a.	Position size, $B	P&L, $M p.a.	Position size, $B
Baseline, no TC, %	200	7.41	80	6.92
Baseline, with TC, %	170	7.41	40	6.92
Conditional, no TC, %	190	10.52	60	9.29
Conditional, with TC, %	170	10.52	50	9.29

Table 11
Inventory risk and EU-open return

Panel A. Zero order imbalance sample
This table shows that EU-open returns remain large after no inventory risk shock at the US close. We rank order imbalance during the last hour of the US session and form two samples, corresponding to 25% to 75% and 40% to 60% of order imbalance (50% is the median imbalance, which is close to zero). We then compute average returns and the corresponding *t*-statistic on the next day for EU-open and the overnight session prior to it.

Order imbalance		Pre-EU-open		EU-open	
Percentile	Average OI, %	Return, %	t-stat	Return, %	t-stat
25% - 75%	0.40%	-0.78	-0.44	6.70	4.69
40% - 60%	0.42%	-4.39	-1.37	8.44	3.39

Panel B. Uncertainty or price pressure?
This table conducts a direct horse race between inventory risk and uncertainty resolution. It shows how EU-open returns depend on change in VIX and order imbalance at the US close (from 3:15 pm to 4:15pm). Control variables in the last column are measured at the previous close and include short-term Treasury rate, term spread, TED spread, bull-bear spread from AAII Investor Sentiment Survey, Baker and Wurgler (2006) sentiment, University of Michigan consumer sentiment index, and a weekend indicator. *t*-statistic is adjusted for autocorrelation and heterogeneity. The sample is smaller due to the availability of intraday VIX index data.

	EU-open return			
	(1)	(2)	(3)	(4)
VIX change	0.3089***		0.3027***	0.3031***
	[3.7]		[3.1]	[3.1]
Order imbalance		-1.1016***	**-0.091**	-0.0691
		[-5.8]	[-0.3]	[-0.3]
Controls	-	-	-	+
Intercept	0.0813***	0.0743***	0.0812***	0.0163
	[5.5]	[5.0]	[5.5]	[0.1]
R^2	0.072	0.019	0.072	0.077
Num. Obs.	2,675	2,675	2,675	2,675

Figure 2

Trading activity and liquidity around the clock

This figure shows how trading activity and liquidity change over a day. Volatility (Panel A) is computed as an annualized standard deviation across one minute realized returns across all days. Trading volume (Panel B) is in future contracts per minute. Volume is shown in log scale as it is extremely skewed. Market depth (Panel C) is an average of sizes at the best bid and ask. The bid-ask spread (Panel D) is in ticks. Average trade size (Panel E) is trading volume in contracts divided by the number of trades. Plots are shown at one-minute frequency. Vertical dashed lines indicate the European and US market open times.

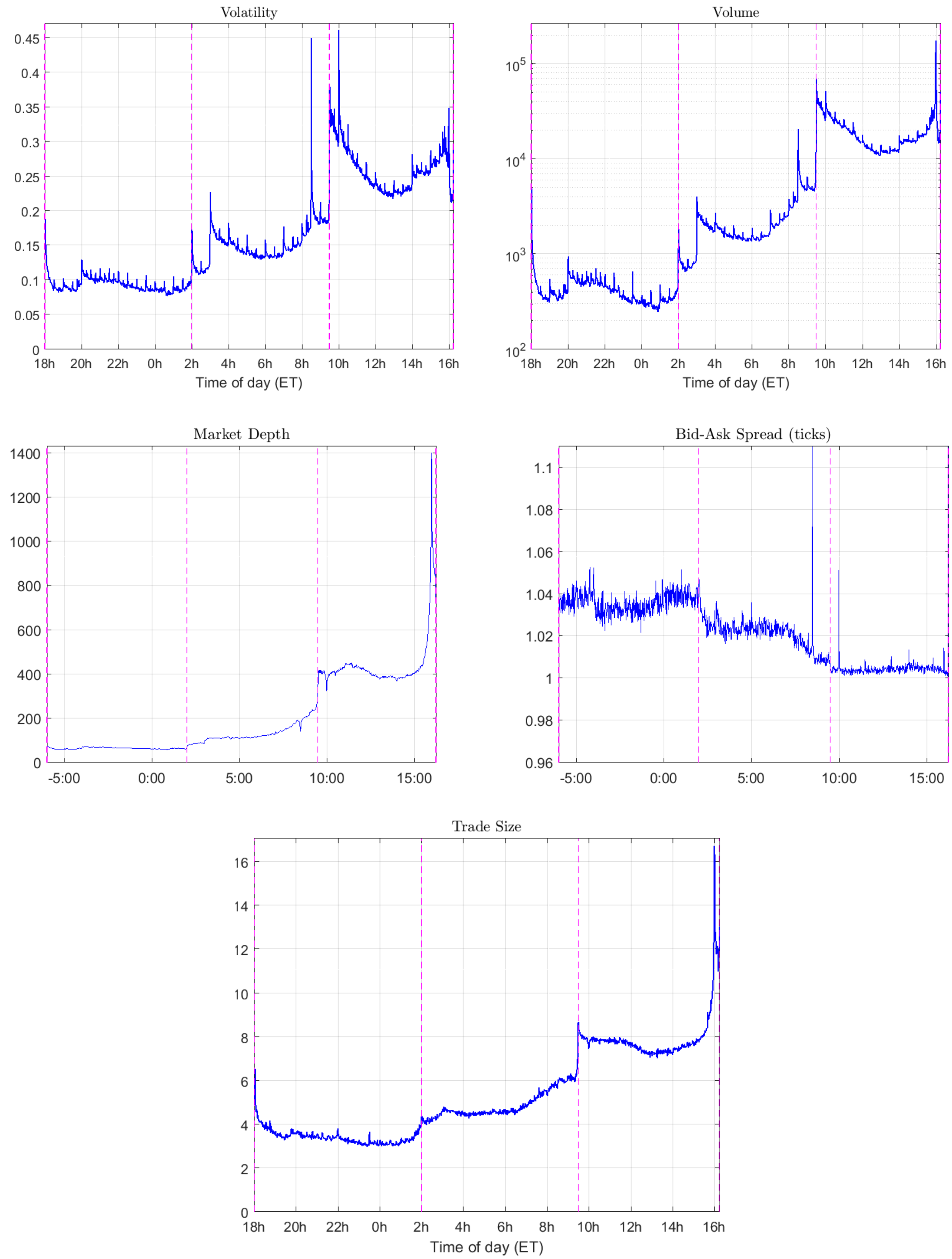


Figure 3
Subperiod returns with confidence intervals

This figure shows how cumulative return varies over a day with corresponding 95%-confidence intervals in grey. The day is split into four intervals: 6:00 pm to 11:30 pm (Asia pre-EU-open), 11:30 pm to 3:30 am (EU-open), 3:30 am to 2:00 pm (EU and US), 2:00 pm to 6:00 pm (US close). Cumulative return is reset to zero at the start of each interval. Confidence intervals expand over time as volatility accumulates.

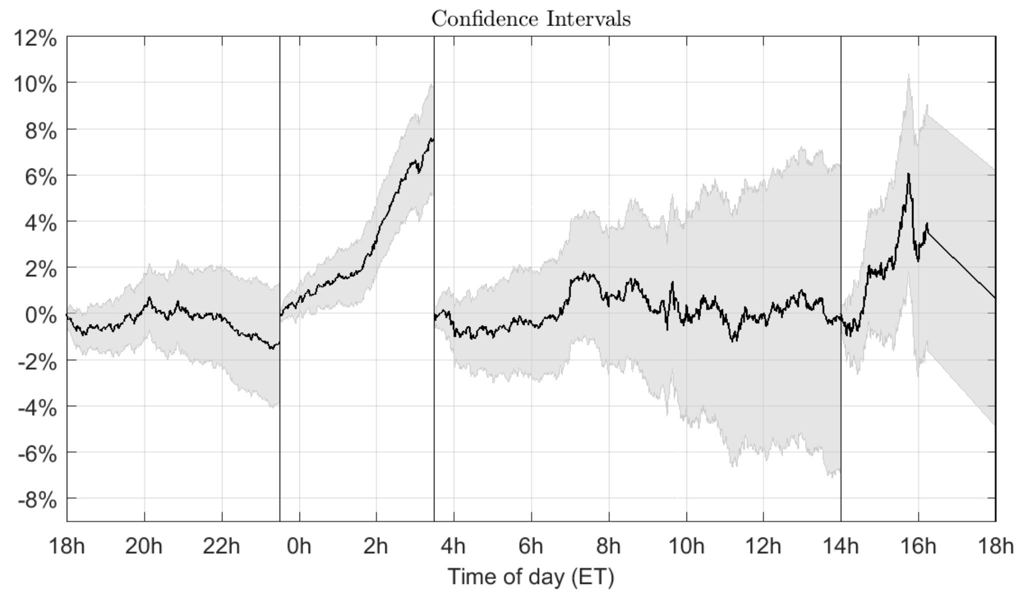
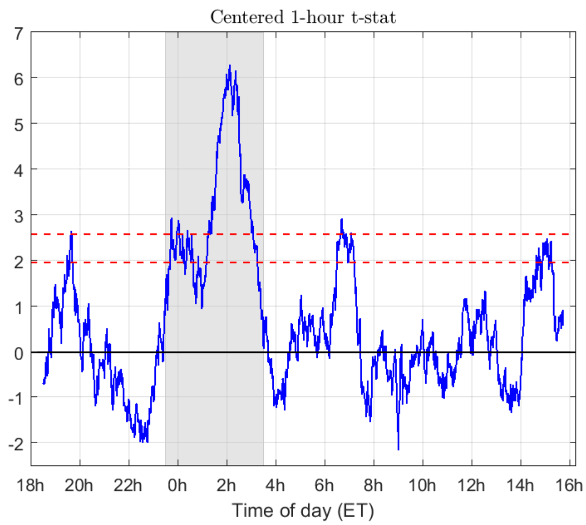


Figure 4
What other intervals have significant returns?
Left (right) panel shows a centered moving average for one-hour (four-hour) cumulative market return during a day. Moving averages are computed at one-minute step. Horizontal dashed lines indicate the 5% and 1% statistical significance levels; *t*-statistic is computed to account for heteroscedasticity and autocorrelation. EU-open period is shaded grey. Market return is computed from E-mini S&P future prices.



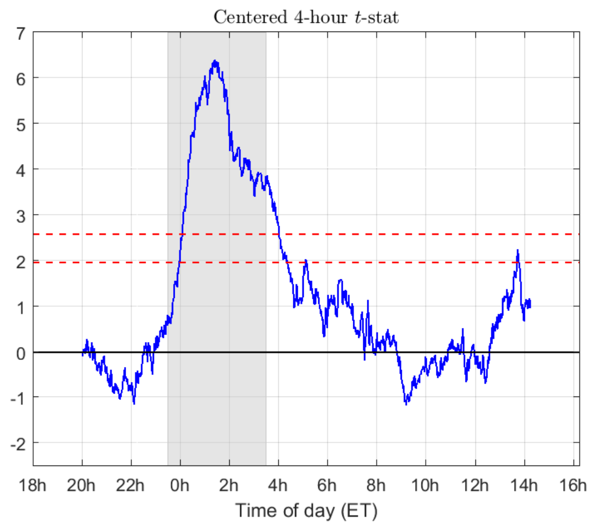


Figure 5
Excess market return and its *t*-statistic over the sample period
Top panel shows a two-year moving average for cumulative market return for EU-open (blue, stable line) period and the rest of the day (RoD, green, volatile line) over the sample period from 2004 to 2018. Vertical dashed lines indicate the 2008 financial crisis (August 1, 2007 to April 1, 2009). Bottom panel repeats the analysis for *t*-statistics of the cumulative market return. Horizontal dashed lines indicate the 5% and 1% statistical significance levels. *t*-statistic is computed to account for heteroscedasticity and autocorrelation. Market return is computed from E-mini S&P future prices.

Figure 6

Europe versus Asia daylight saving time change

This figure shows cumulative market return (left panels) and minute-by-minute trading volume (right panels) around EU-open. Top panel reports results in US time (ET), while bottom panel reports the same results but in Asian time (JST). Asia does not observe daylight savings time (DST), while the US and Europe do. "Summer" is the period when both US and Europe observe DST (i.e., shift one hour ahead compared to the rest of the year ("Winter")). The return and volume patterns remain the same in US time but shift in Asian time. ET is local Eastern Time, equal to Eastern Standard Time (EST) in winter and Eastern Daylight Savings Time (EDT) in summer; JST is Japan Standard Time. Trading volume is the number of contracts per minute. Cumulative return is annualized. Vertical solid lines indicate the EU-open period.

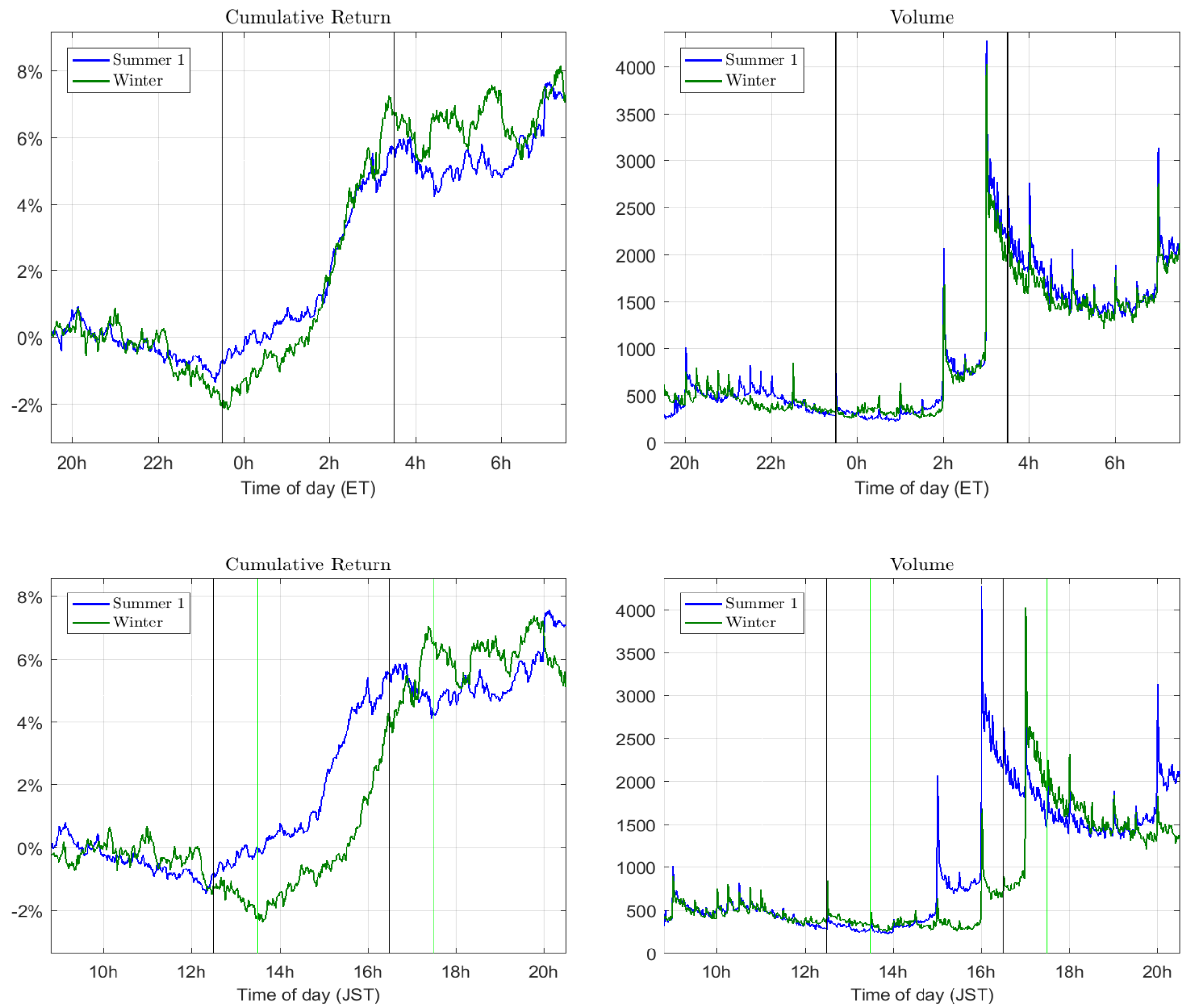
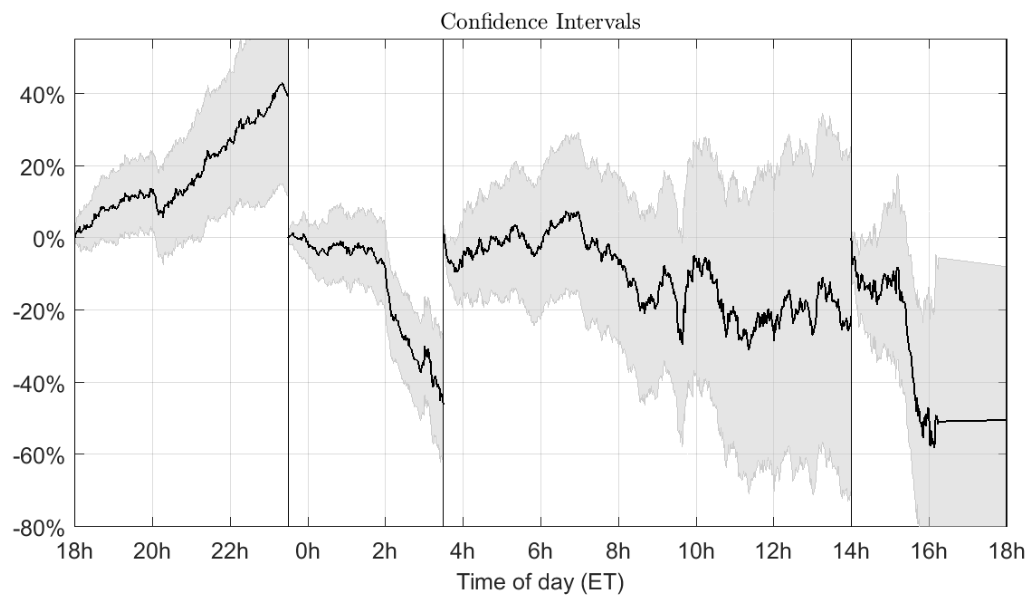


Figure 7

VIX futures returns around the clock

Top panel shows how cumulative return for VIX futures varies over a day with corresponding 95%-confidence intervals (in grey). The day is split into four intervals: 6:00 pm to 11:30 pm (Asia pre-EU-open), 11:30 pm until 3:30 am (EU-Open), 3:30 am to 2:00 pm (EU and the US), 2:00 pm to 4:15 pm (US-close). Cumulative return is reset to zero at the start of each interval. Confidence intervals expand over time as volatility accumulates. Extended hours for VIX futures start spanning EU-open on July 2014, and the sample ends in July 2018. The bottom panel show a centered moving average for four-hour cumulative VIX future return during a day. Horizontal dashed lines indicate 5% and 1% statistical significance levels. *t*-statistic is computed to account for heteroscedasticity and autocorrelation. EU-open period is shaded grey. Plots are shown at 5-minute frequency.



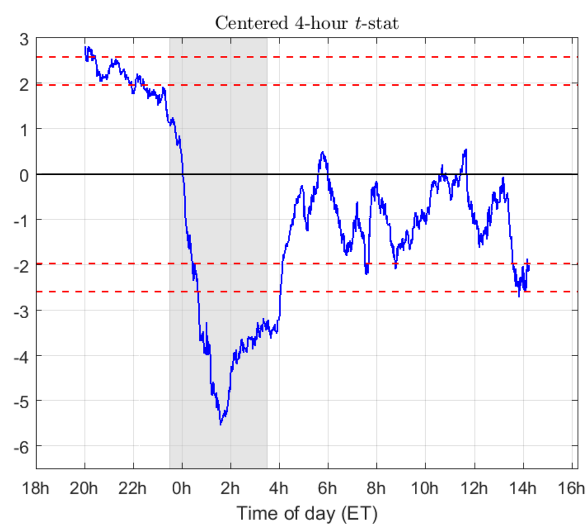


Figure 8
Variance ratio price efficiency test
This figure shows how return variance depends on time of the day when prices are taken to compute 24h returns and then their variance. Variance at time *t* is computed as average over all days of squared returns from *t* to *t+24h*. We then report a ratio of variance at time *t* to overall daily average variance (over all starting times). For example, 1.08 at 0:00h means that variance is 8% higher than average for the 18:00-to-18:00 returns. Variance ratio is often used as measure price noise.

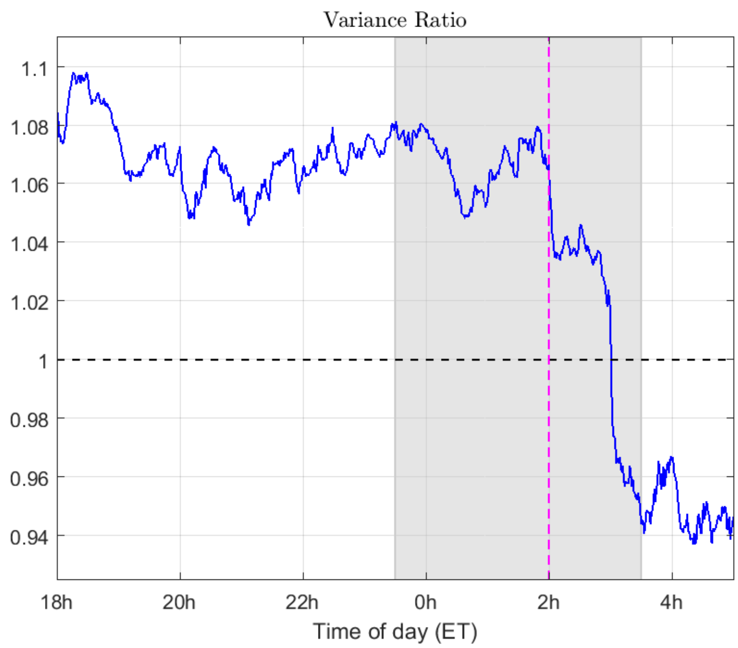


Figure 9
Weekends versus weekdays
This figure compares cumulative market return (left panel) and minute-by-minute trading volume (right panel) during a day for weekends (Mon, Friday-to-Monday) with regular weekdays (non-Mon). There is little difference between the two. Cumulative return is annualized. Solid vertical dashed lines mark the EU-open period boundaries. Vertical dashed lines separate the three trading sessions.

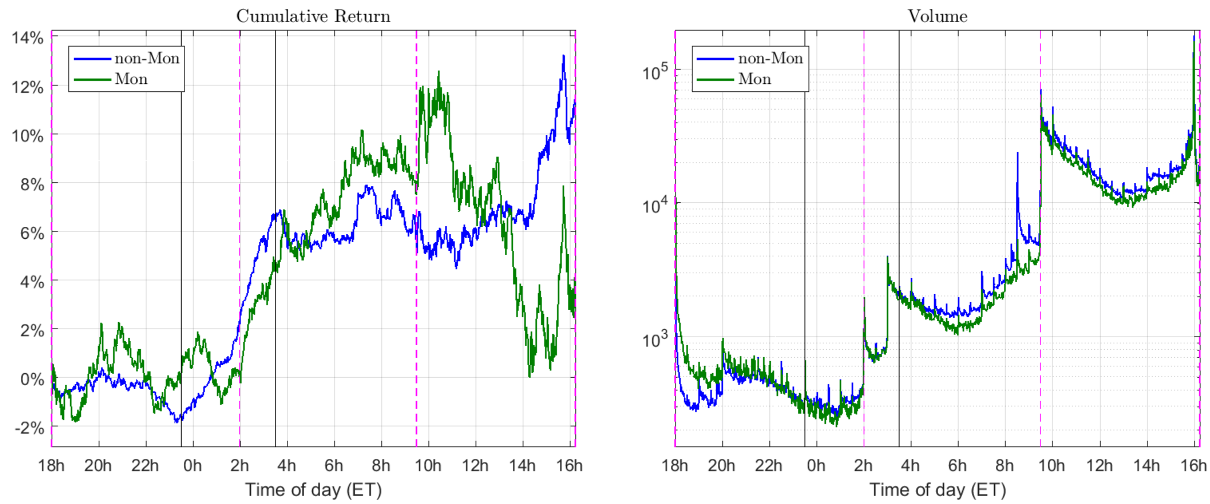
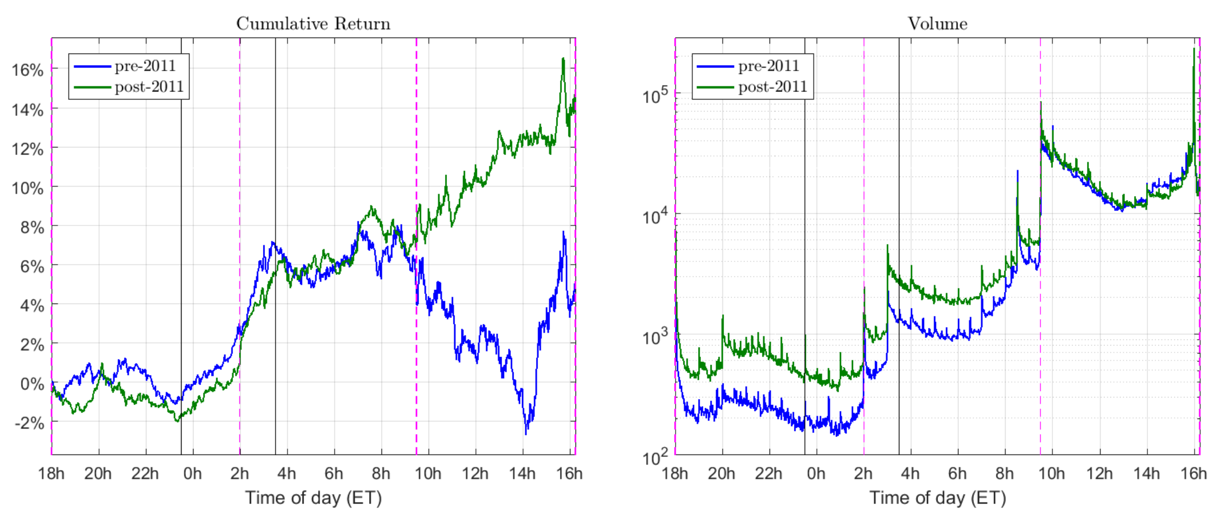


Figure 10
First and second part of the sample
This figure compares cumulative market return (left panel) and minute-by-minute trading volume (right panel) during a day for the first (pre-2011) and second (post-2011) part of the sample period. Trading volume increased markedly during post-2011, but the EU-open return pattern remained unchanged.
Cumulative return is annualized. Solid vertical dashed lines mark the EU-open period boundaries. Vertical dashed lines correspond to the European and US market open times.



Internet Appendix

This appendix describes how volatility, volume, and liquidity change over a day and presents additional figures and tables.

IA.1 Volume, volatility, and liquidity around the clock

We focus on average market return, but other market variables such as volatility, volume, the bid-ask spread, and market depth also show interesting patterns around the clock. Figure 2 shows how these four variables change over a day at a one-minute resolution. As expected, volatility and volume generally follow each other, but volume changes are much more dramatic. Therefore, it is shown on a log scale. Several episodes stand out. First, US macro announcements correspond to the two biggest (one-minute) volatility spikes at 8:30 am and 10:00 am; however, the spikes quickly revert to a normal volatility level. Volume spikes are less pronounced. Perhaps macro news affects prices but does not trigger large portfolio rebalancing. Market depth decreases while the bid-ask spread increases as liquidity providers avoid announcement uncertainty. Even though these two minutes that contain US macro news have high volume and volatility, average returns are not significantly different from zero during these periods.

Second, volatility and volume are U-shaped during the US session and pre-US European session. For the pre-US European session, volume is much higher approaching US open as US investors arrive to the market. For the US session, volume is the highest at 4:00 pm then drops during the last 15 minutes. The Asian session's pattern differs. Volatility and volume spike at Hong Kong/China open and then gradually decrease until European open. The European session has its first spike when Frankfurt opens. Then, volume quickly reverts to the Asian level. However, a much bigger spike occurs during London open, which makes volatility and volume permanently higher than in pre-period. Third, volatility and volume spike at 6:00 pm when GLOBEX re-opens after a technical break and investors trade on the information accumulated during the break. Finally, both measures have small spikes at every round-numbered half-hour due to investor preference for round numbers. Andersen, Bondarenko, Kyle, Obizhaeva (2018) use intraday trading invariance hypothesis to explain relationship between volume, volatility, and trade size in the E-mini S&P 500 futures market.

Importantly, one of the biggest spikes in trading volume during the Asian session occurs exactly at 11:30 pm, right at the start of the EU-open period. This spike is comparable to the one occurring during Hong Kong/China open. Like the Hong Kong/China open volatility spike, the volume quickly reverts to normal. The corresponding volatility spike is much smaller and is comparable to other round-hour spikes. During EU-open, the two major spikes occur during European and London open. Volatility reverts to Asian levels quickly after the spike at European open, but volume remains high. On the other hand, London open permanently elevates volatility and volume after the initial spike.

Market depth and bid-ask spread are obviously related to volatility and volume but also have individual patterns. Market depth increases exponentially in the period approaching US close, reaching levels that are three times higher than during the rest of the US session. The bid-ask spread is almost always one tick. It drops during China/Hong Kong open, increases slightly during EU-open, but decreases after Europe opens. The spread has two large spikes during US macro announcements.

Table IA.1

Excess market returns for intraday intervals

This table reports essential statistics for E-mini S&P future returns including average return, *t*-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. All these measures are computed from annualized log returns and, when applicable, are reported as percent. We also report return distribution percentiles, which are not annualized. Intraday intervals include the overnight session before EU-open, first and second halves of EU-open, Asian, European, and US sessions, the period between US close (4:15 pm) and E-mini re-open (6:00pm), and finally the entire day in the last column. Max drawdown is the difference between a portfolio's point of maximum return and any subsequent low point of performance.

	Asia pre-EU-open	EU-open 1st Half	EU-open 2nd Half	Asia	Europe	US	Post US-close	Total
	6:00 pm-11:30 pm	11:30 pm-1:30 am	1:30 am-3:30 am	6:00 pm-2:00 am	2:00 am-9:30 am	9:30 am-4:15 pm	4:15 pm-6:00 pm	6:00 pm-6:00 pm
Average return, % p.a.	-1.25	1.70	5.90	1.80	4.39	3.44	-2.83	6.80
t-statistic	-0.95	2.51	5.85	1.21	2.16	0.89	-2.89	1.39
Standard deviation, %	5.01	2.57	3.84	5.67	7.73	14.75	3.73	18.63
Sharpe ratio, p.a.	-0.25	0.66	1.54	0.32	0.57	0.23	-0.76	0.36
Skewness	-2.14	-0.23	1.46	-1.37	-0.13	-0.50	-1.68	-0.42
Kurtosis	37.56	36.22	42.00	35.02	11.33	15.27	84.37	16.80
Min, %	-4.06	-2.11	-2.58	-5.41	-3.23	-9.15	-4.61	-12.01
5%	-0.41	-0.18	-0.28	-0.47	-0.71	-1.43	-0.24	-1.73
25%	-0.10	-0.04	-0.07	-0.11	-0.18	-0.35	-0.06	-0.39
50%	0.00	0.00	0.02	0.00	0.02	0.06	0.00	0.08
75%	0.11	0.05	0.11	0.13	0.23	0.43	0.04	0.54
95%	0.37	0.20	0.35	0.45	0.71	1.26	0.22	1.57
Max, %	2.94	1.87	3.81	3.11	3.70	7.53	3.69	11.28
Max drawdown, %	25.35	3.37	8.44	10.35	30.28	44.55	0.00	61.89

Table IA.2
Trading activity over time

The table shows trading activity for E-mini S&P futures during Asian, European, and US sessions by year. Note how Asian share of trades jumps from 0.07% in 2002 to 1.28% in 2004. The last three columns sum up to 100%.

	Total number of trades, 000s				Percentage of total		
	Asia	Europe	US	Total	Asia	Europe	US
1998	0.08	3.01	44.78	47.87	0.18	6.29	93.53
1999	0.08	4.77	93.51	98.37	0.08	4.85	95.07
2000	0.08	5.87	147.74	153.69	0.05	3.82	96.13
2001	0.14	10.06	220.87	231.07	0.06	4.35	95.58
2002	0.26	16.90	362.32	379.49	0.07	4.45	95.48
2003	2.53	25.04	400.09	427.67	0.59	5.86	93.55
2004	7.40	38.47	532.50	578.37	1.28	6.65	92.07
2005	7.03	42.80	562.73	612.56	1.15	6.99	91.86
2006	5.32	33.24	313.24	351.79	1.51	9.45	89.04
2007	13.60	81.73	597.10	692.43	1.96	11.80	86.23
2008	40.43	213.13	1320.61	1574.16	2.57	13.54	83.89
2009	45.06	231.63	1329.34	1606.03	2.81	14.42	82.77
2010	78.13	459.68	2208.24	2746.05	2.85	16.74	80.42
2011	114.85	577.09	2474.45	3166.39	3.63	18.23	78.15
2012	92.50	469.62	1905.24	2467.36	3.75	19.03	77.22
2013	84.88	363.54	1957.63	2406.05	3.53	15.11	81.36
2014	79.38	394.30	2090.03	2563.70	3.10	15.38	81.52
2015	72.59	239.15	1212.90	1524.64	4.76	15.69	79.55
2016	90.11	209.65	889.17	1188.93	7.58	17.63	74.79
2017	46.87	107.82	559.94	714.63	6.56	15.09	78.35
2018	106.59	203.65	1128.66	1438.90	7.41	14.15	78.44

Table IA.3
Market return for the extended sample by year

This table reports several statistics for E-mini S&P futures returns by year. While the main analysis is based on the sample from 2004 to July 2018, this table extends the sample to 1998. However, prior to 2004 the Asian session was very illiquid (see Table IA.2). Furthermore, prior to July 2003 E-mini S&P only traded starting from 1:00 am. That is, the Asian session was open for only 1 hour instead usual 8 hours and EU-open was open for 2.5 hours instead of 4 hours. After July 2003, 2:00 am the trading hours were extended to the current 6:00 pm or nearly 24 hours. The statistics include average return, *t*-statistics, standard deviation, and Sharpe ratio. All these statistics are based on annualized log returns (period return times 252) and, when applicable, are reported as percent. The entire trading day is split into EU-open (from 11:30 pm to 3:30 am) and the rest of the day (6:00 pm to 11:30 pm and 3:30 am to 6:00 pm). *t*-statistic is computed to account for heteroskedasticity and autocorrelation. Last two rows report averages for two subsamples.

	EU-open				Rest of the day			
	Exp. return	Std. dev.	Sharpe ratio	*t*-statistic	Exp. return	Std. dev.	Sharpe ratio	*t*-statistic
1998	3.11	3.31	0.94	0.94	17.33	21.43	0.81	0.81
1999	4.64	2.09	2.22	2.22	9.02	18.67	0.48	0.48
2000	11.76	2.22	5.29	5.29	-28.39	22.80	-1.25	-1.25
2001	-1.52	3.34	-0.46	-0.45	-16.48	20.58	-0.80	-0.79
2002	0.73	4.05	0.18	0.18	-27.73	26.26	-1.06	-1.06
2003	3.25	3.25	1.00	1.00	20.17	16.90	1.19	1.19
Average:								
1998-2003	3.66	3.04	1.53	1.53	-4.35	21.11	-0.10	-0.10
2004-2018	7.65	3.96	2.19	2.15	-0.82	15.81	0.25	0.26

Table IA.4
EU-open first half versus second half

We split EU-open into two two-hour periods: from 11:30 pm to 1:30 am ET (1st half) and from 1:30 am to 3:30 am ET (2nd half). The table reports average annualized return, standard deviation, contract trading volume, and trade size for E-mini S&P 500 futures and VIX futures. The statistics are computed over the period from January 2004 to July 2018 for E-mini S&P 500 futures and over the period from July 2014 to July 2018 for VIX futures. We also report the difference between the two periods and *t*-statistic for the difference, which is computed to account for heteroskedasticity and autocorrelation.

	EU-Open			
	1st half	2nd half	Diff.	*t*-stat.
E-mini S&P return	1.70	5.90	4.21	3.92
E-mini S&P volatility	0.11	0.15	0.04	23.93
E-mini S&P volume, 000s	37.74	132.17	94.43	20.57
E-mini S&P trade size	3.21	4.27	1.05	16.48
VIX return	-4.56	-41.70	-37.14	-3.55
VIX volatility	0.40	0.66	0.26	21.01
VIX volume, 000s	1.84	5.22	3.38	13.58
VIX trade size	3.85	4.80	0.95	5.64

Table IA.5
Asian volume and average returns

For each calendar year, we first compute average returns and volume and then estimate two univariate regressions. The dependent variable is average return (pre EU-open or EU-open). The independent variable is the Asian volume share, defined as the average ratio of the volume for the Asian session to the volume for the entire day (in percent). t-statistics are reported in parentheses.

	Intercept	Asian volume share	*Adj. R^2*	Num. Obs.
Pre EU-open return	1.73	-1.38	18.11%	15
	[0.92]	[-2.18]		
EU-open return	7.37	0.15	-7.39%	15
	[4.38]	[0.24]		

Figure IA.1

Cumulative returns: quote midpoint versus trade price

Average cumulative log returns for E-mini S&P futures over the trading day. For the red line, returns are computed with trading prices as in Figure 1. For the blue line, returns are computed from quote midpoints. The two lines are barely distinguishable. The sample period is from 2006 to 2018 due to availability of quote data.

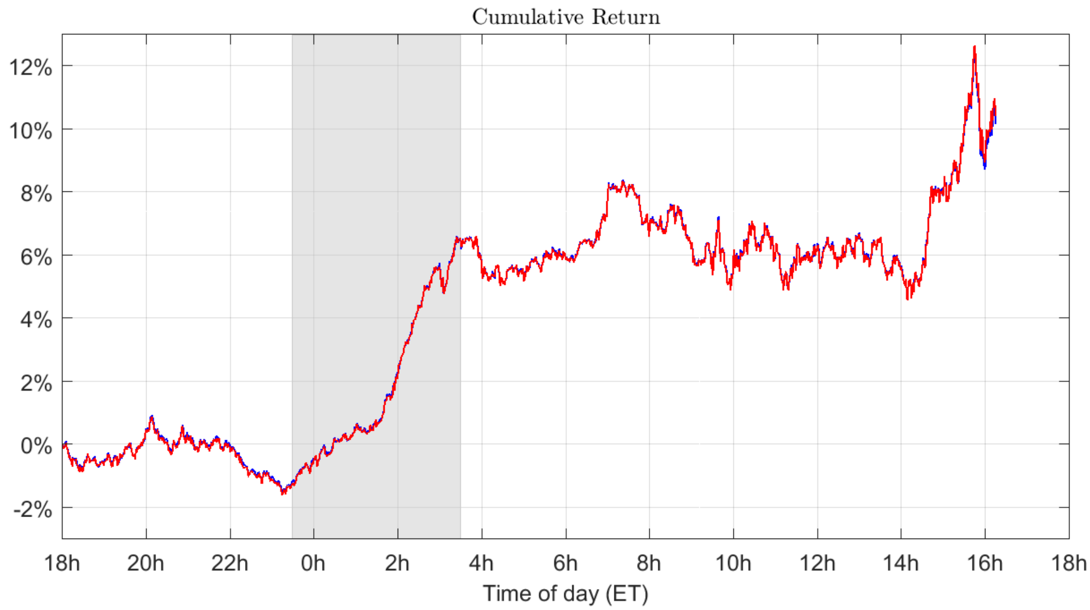
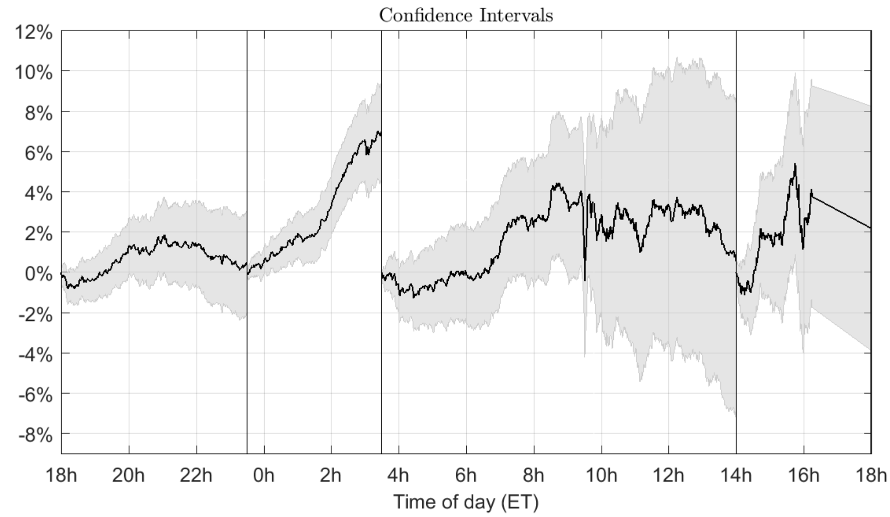


Figure IA.2
Subperiod returns for E-mini Nasdaq-100 and Dow index futures

This figure shows how cumulative return varies over a day with corresponding 95%-confidence intervals in grey. The day is split into four intervals: 6:00 pm to 11:30 pm (Asia pre-EU-open), 11:30 pm to 3:30 am (EU-open), 3:30 am to 2:00 pm (EU and US), 2:00 pm to 6:00 pm (US-close). Cumulative return is reset to zero at the start of each interval. Confidence intervals expand over time as volatility accumulates.

Panel A. E-mini Nasdaq-100



Panel B. E-mini Dow

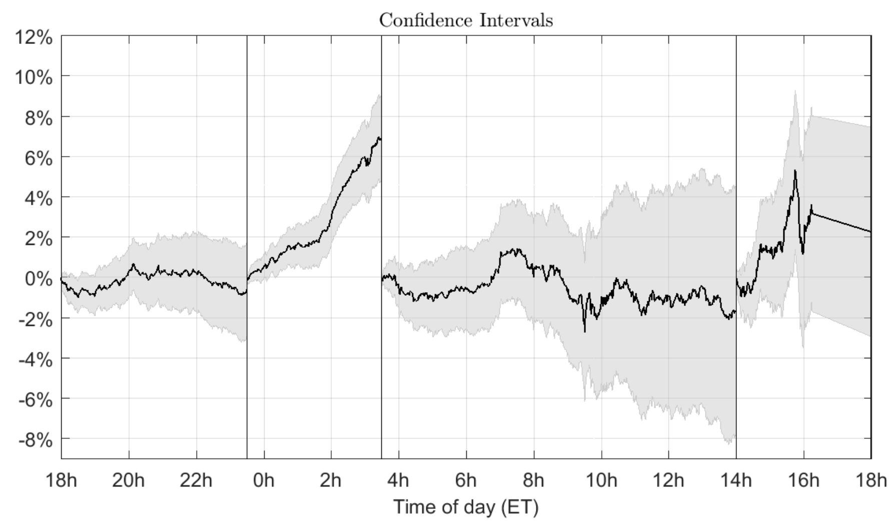
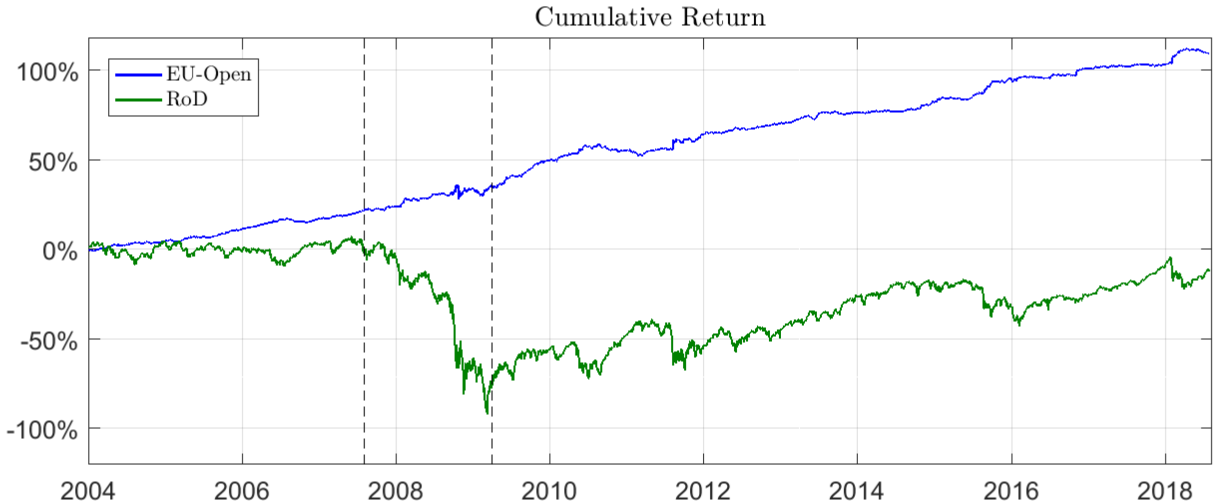


Figure IA.3
Cumulative market return over time

Top panel shows cumulative market return for EU-open (blue, stable line) period and the rest of the day (RoD, green, volatile line) from 2004 to 2018. Vertical dashed lines indicate the 2008 financial crisis (August 01, 2007 to April 01, 2009). Bottom panel shows contribution of EU-open to the total daily return variance. This contribution is computed as a ratio of the realized variance for EU-open to the realized daily variance. Thick red line shows a two-year moving average. Market return is computed from E-mini S&P future prices.



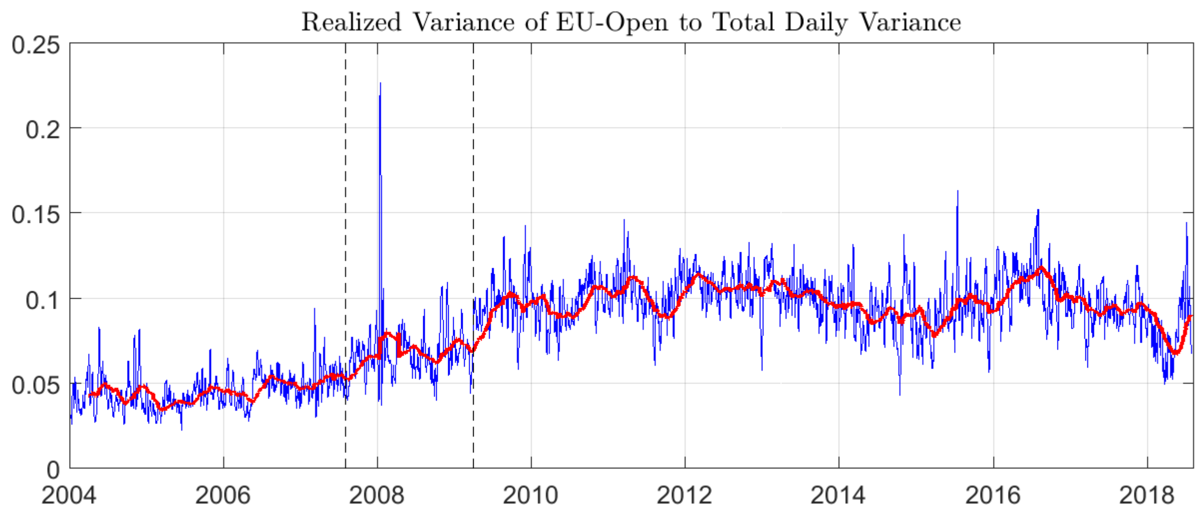


Figure IA.4
Returns in calendar and variance time

This figure shows cumulative market return over a trading day in regular calendar (left) and variance (right) clocks. In variance clock, the time slows down or speeds up so that the rate of the accumulated return variance is constant. That is, the cumulative return trajectory does not change but the horizontal axis is deformed to reflect varying speed of stochastic clock. Market return is computed from E-mini S&P future prices. Cumulative return is annualized by multiplying period return by 252. Vertical dashed lines indicate the European and US open times; grey area indicates the EU-open period.

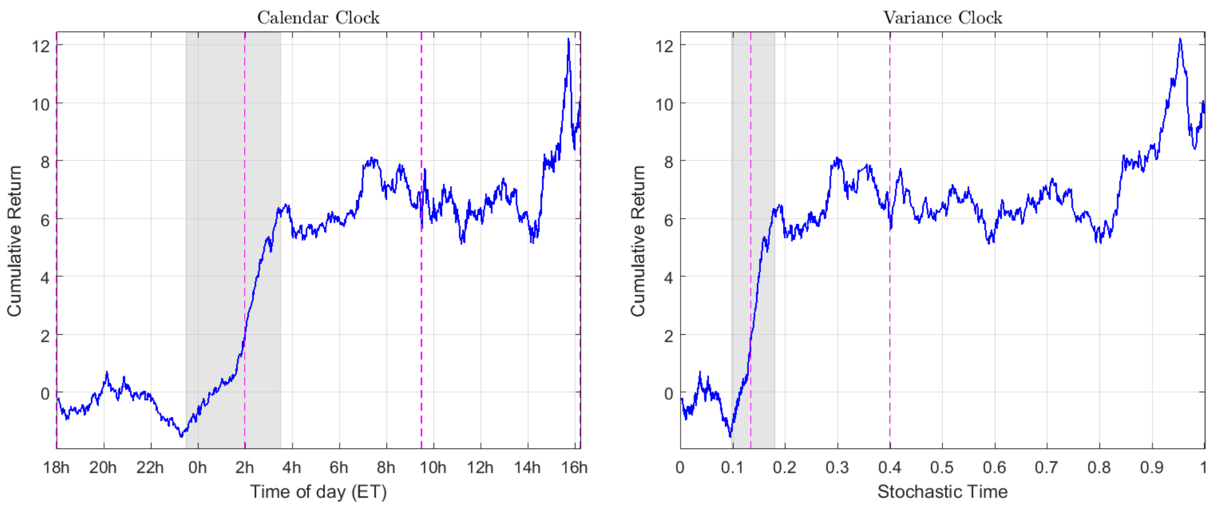


Figure IA.5

Cumulative returns for VIX futures over the sample period

Top panel shows a two-year moving average for cumulative VIX futures return during the Asian session before EU-open (green, increasing line), EU-open (blue, decreasing line) and the rest of the day post EU-open (red, volatile line) over the sample period from July 2014 to July 2018.

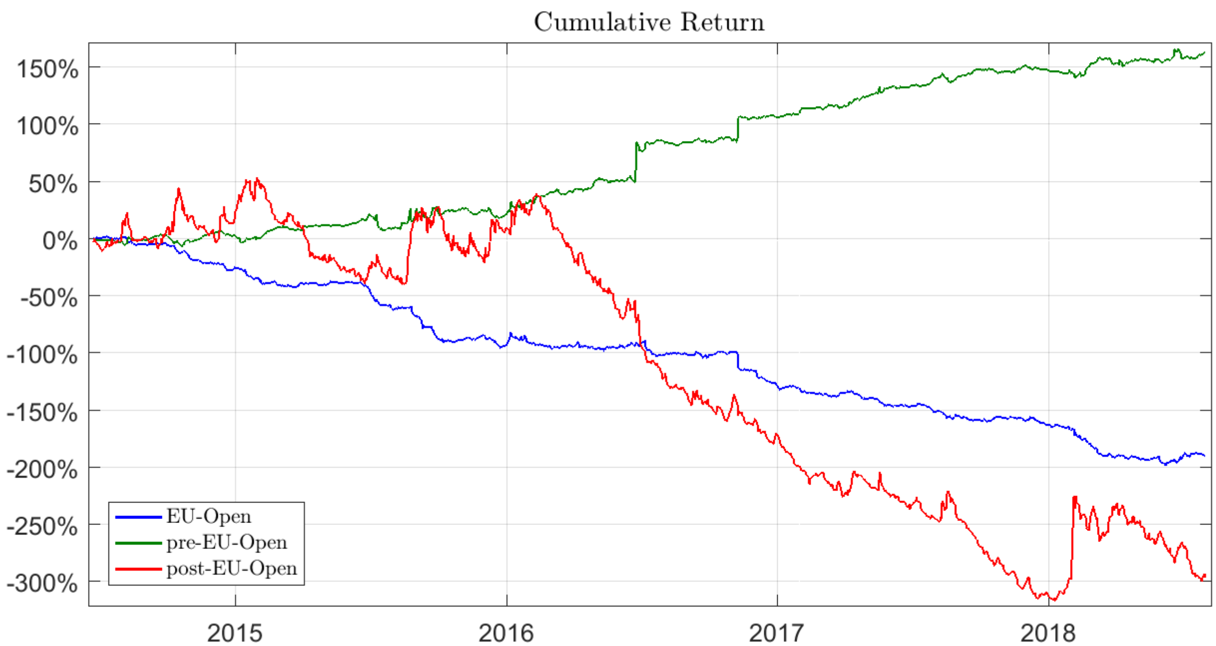


Figure IA.6

Excess VIX futures return and its *t*-statistic over the sample period

Top panel shows a two-year moving average for cumulative VIX future return for overnight session prior to EU-open (green line, around +50%), EU-open (blue line, around -50%), and post-EU-open (rest of the day, red volatile line) periods over the sample period from July 2014 to July 2018. Bottom panel repeats the analysis for *t*-statistic of the cumulative VIX future return. Horizontal dashed lines indicate the 5% and 1% statistical significance levels. *t*-statistic is computed to account for heteroscedasticity and autocorrelation. Log return is computed from front-month VIX future prices.

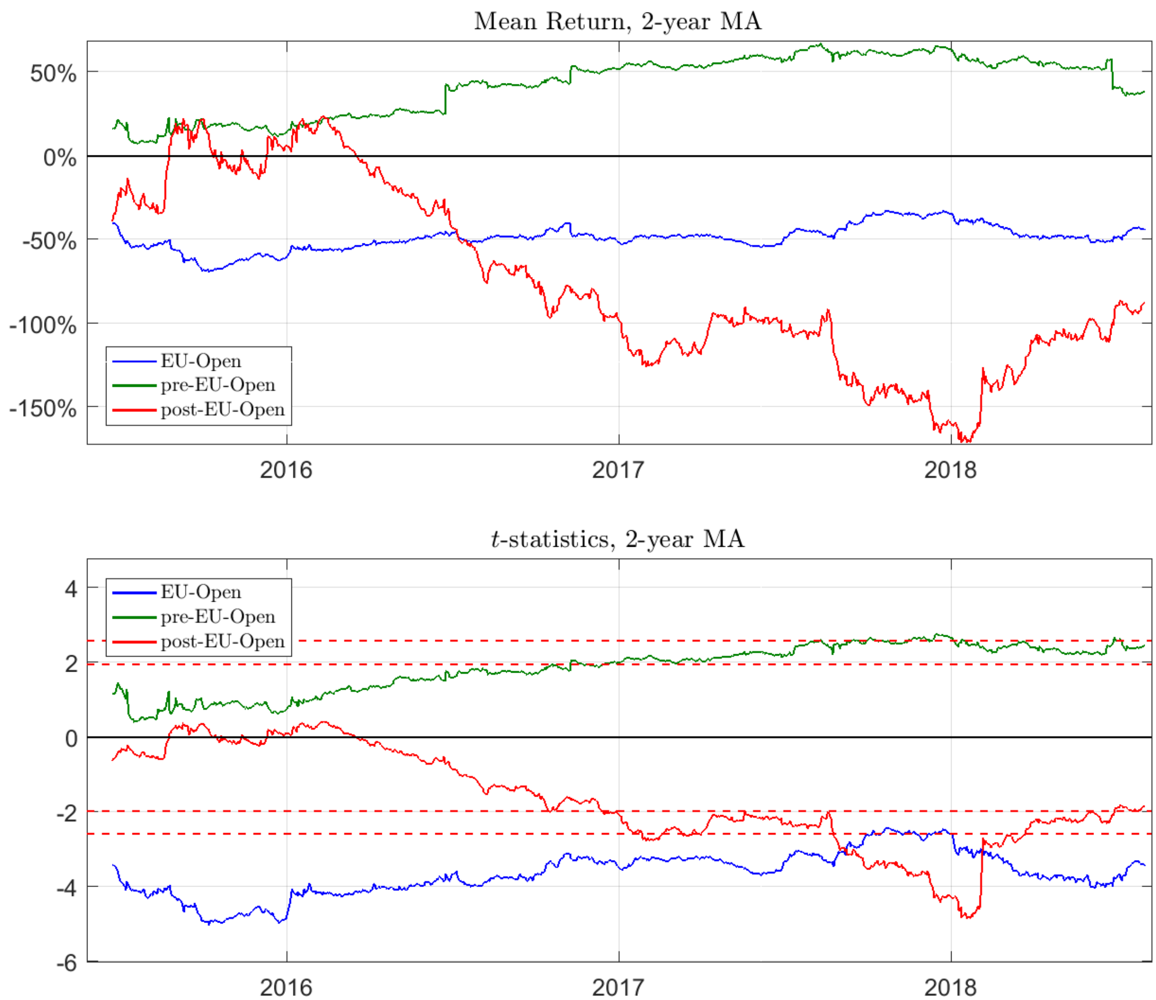


Figure IA.7

Uncertainty and returns during EU-open

Left panel plots E-mini S&P and VIX futures cumulative returns (blue and green lines). Right panel shows trading volume and realized volatility (blue and green lines). Vertical solid lines denote EU-open. Dashed vertical line denotes Frankfurt open.

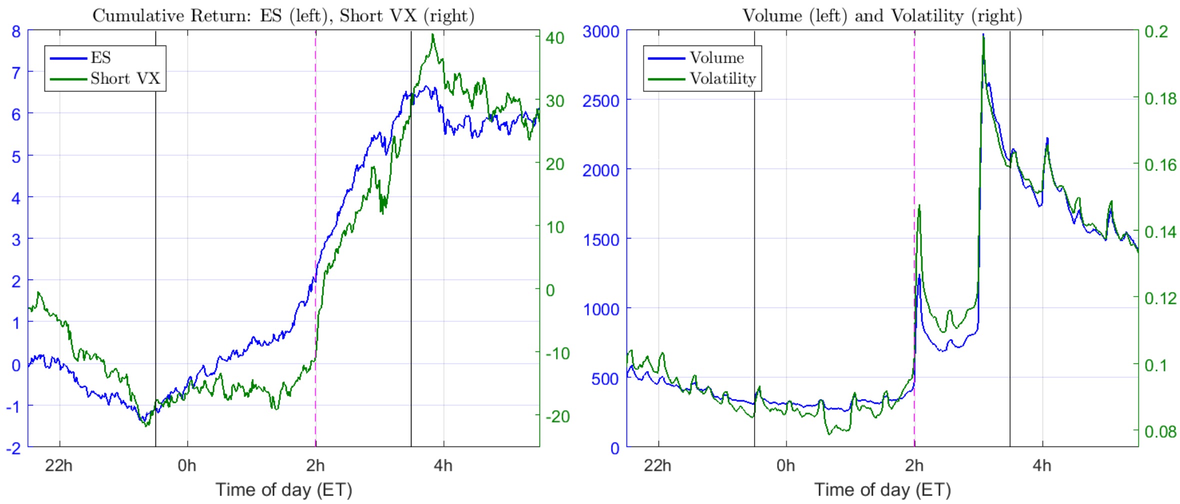


Figure IA.8
Cumulative returns for sample with zero order imbalance

This figure shows cumulative market return over a trading day for the sample with close-to-zero order imbalance on the prior US close. We compute order imbalance during one hour around prior to the US close (3:15 pm to 4:15 pm) and pick days that are between 40% and 60% (they thus have low order imbalance). Order imbalance is between -1 and 1 and is proxy for inventory shocks at the US close. Market return is computed from E-mini S&P future prices. Cumulative return is annualized by multiplying period return by 252. Vertical dashed lines indicate the European and US open times; solid lines mark the EU-open period.

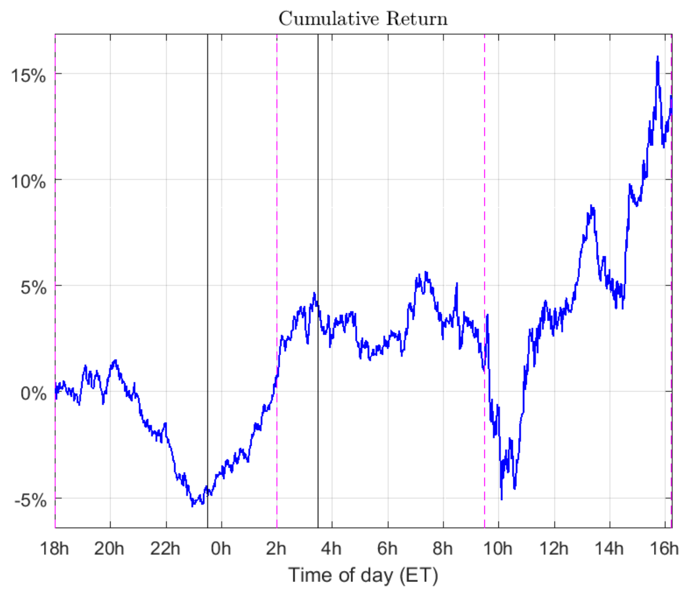


Figure IA.9

Cumulative returns for baseline and conditional strategies over time

The strategy buys E-mini future at the start of EU-open and closes position at the end of EU-open. Top and bottom panels show cumulative returns before and after transaction costs, respectively. Conditional strategy trade only on 40% of days with high expected EU-open return. Each trade involves the same capital. Transaction costs include the bid-ask spread and the round-trip exchange fees and commissions. Vertical dashed lines mark the 2008 financial crisis.

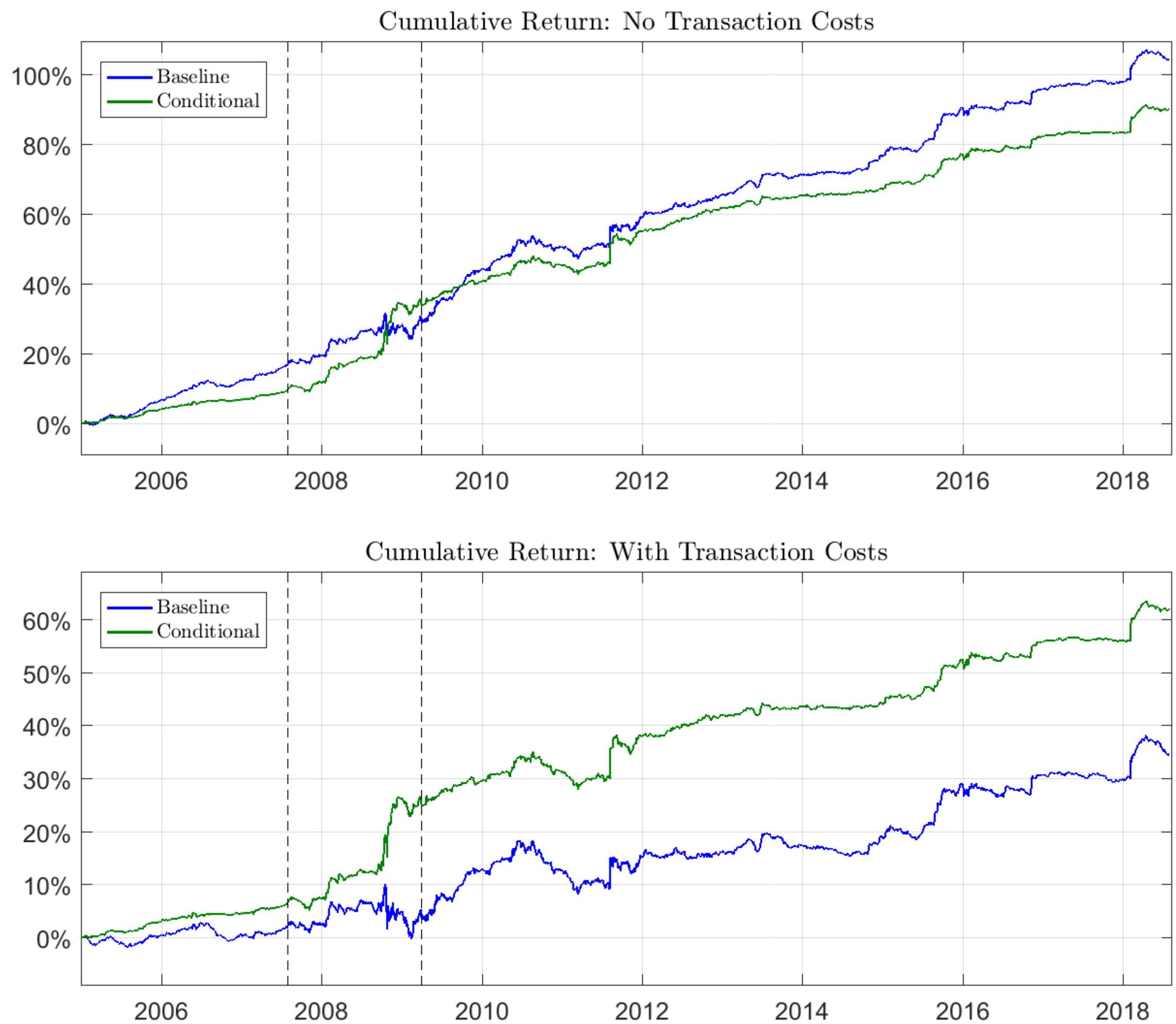
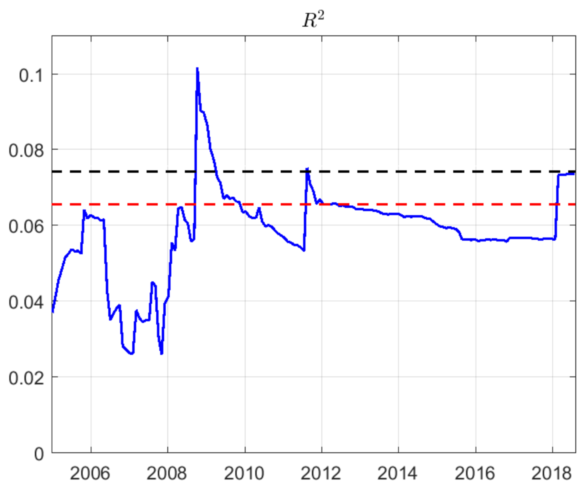


Figure IA.10

Conditional trading strategy

The figure shows the R^2 of the predictive model (left panel) and fraction of days when the conditional strategy trades (right panel). The model use as predictors daily change in VIX and Asian volatility. We report three types of R^2. The blue, time-varying line shows (in-sample) R_t^2 of the predictive model estimated in month *t*, with expanding estimation window. The two horizontal dashed lines indicate the in-sample and out-of-sample R_{OS}^2 estimated for the full sample: R_{IS}^2 (black) and R_{OS}^2 (red). The out-of-sample R_{OS}^2 is computed following the approach in Campbell and Thompson (2008). The conditional strategy trades on about 40% of days (indicated with the dashed line on the right panel) for which the model predicts higher expected EU-return. The fraction of days selected is shown as a 3-month moving average.



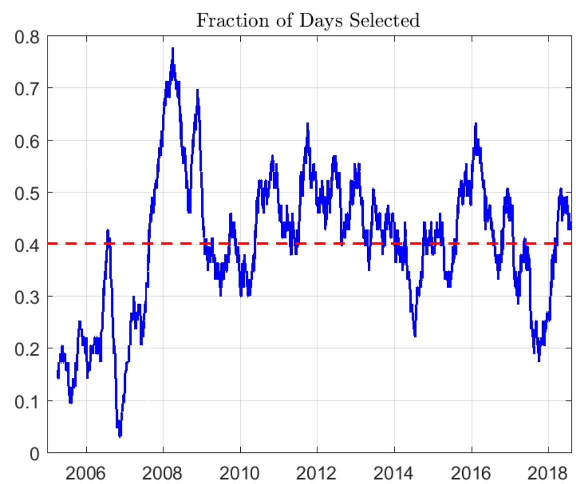


Figure IA.11

Market return on FOMC announcement days.

The figure shows average cumulative market return (from S&P 500 E-mini futures) as a function of time of the day (in ET). We annualize return as period return times eight, the number of FOMC announcements in a year. FOMC statement released at or a few minutes after 2:15 p.m. ET. Dashed lines denote Frankfurt open, US open and close. Solid black lines denote EU-open. The sample period is from January 2004 to July 2018.