Market Return Around the Clock: A Puzzle

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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 Asian markets' close and European open account for the entire average market return. This period's Sharpe ratio is extremely high as overnight volatility is low. Its returns are consistently positive every year and survives transaction costs. Remarkably, average returns are zero during the remaining 20 hours and almost all sub-intervals. We attribute high returns around European open to the uncertainty resolution as European investors help process information accumulated during Asian trading hours. Consistent with this hypothesis, VIX future returns are positive during the Asian session and highly negative around European open.

JEL Classification: G12, G13, G14

Keywords: Market return, intraday data, information asymmetry, index futures

1. Introduction

We study how excess market return as reflected by S&P 500 index changes over day and night. This exercise is possible because E-mini S&P 500 futures are actively traded at night.[1] E-mini S&P futures returns equal excess returns on S&P 500 index. The E-mini overnight session starts at 6 p.m. (Eastern Time, EST) and spans almost 24 hours with a short break after U.S. close. Figure 1 shows how cumulative returns of E-mini futures depend on the time of the day. Average returns during one period clearly stands out. After being zero-flat during the first part of the overnight session, the cumulative returns rapidly increase between 11:30 p.m. and 3:30 a.m. and afterwards become flat again. During the 2004 to 2018 sample period, these four hours have a 7.6% annualized return. We call this period "EU-open", as it corresponds to deep night in the U.S., late afternoon in Asia, and early morning in Europe. Asian markets close and European markets open during EU-open. In contrast, returns during the rest of the day are only -0.8% p.a., or virtually zero, and is flat for the entire day except around U.S. close.[2]

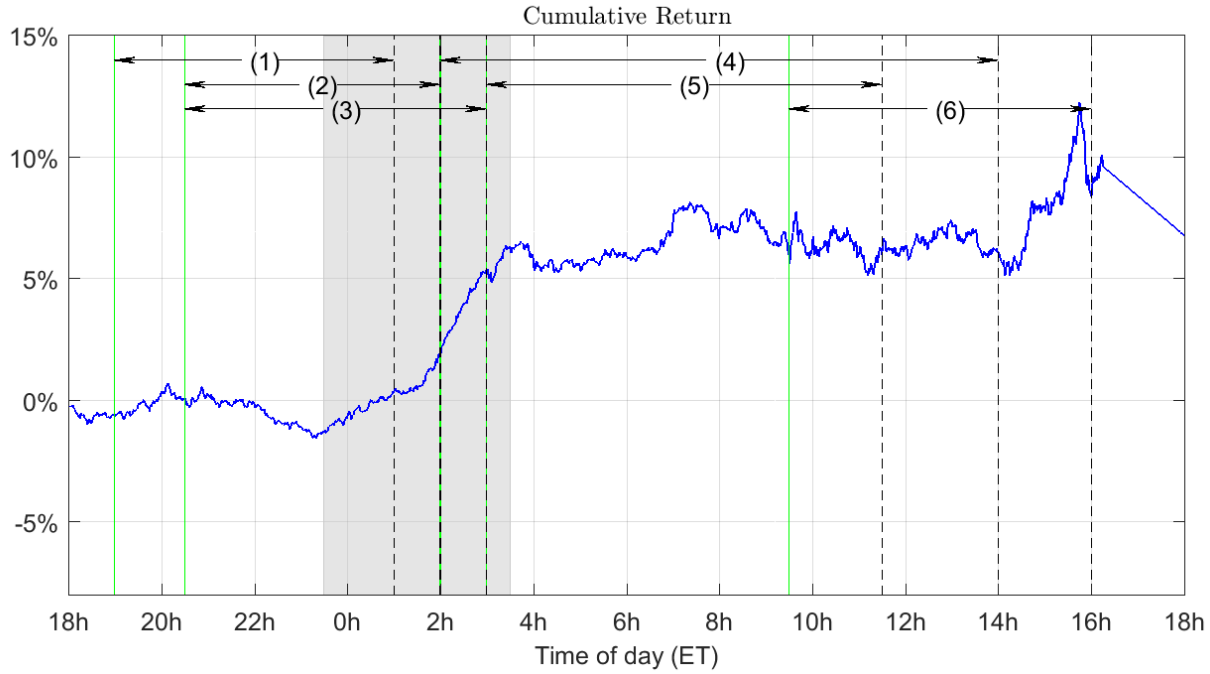


Figure 1. Annualized average cumulative log returns for S&P 500 E-mini futures as a function of time of the day. Arrow lines denote open and close times for major equity markets (Japan, China, Hong Kong, Frankfurt, London, and the U.S.). The market is mostly closed from 4:15pm to 6pm. EU-open period is in grey. Time of day is in Eastern Standard Time (EST).

[1] S&P 500 e-mini futures provide an excellent proxy for excess market return, which is commonly-used in the market return predictability literature. By no arbitrage, it closely tracks the underlying index. Hasbrouck (2003) shows that E-mini futures lead the spot index and account for most of price discovery.

[2] Our sample starts in 2004 because most E-mini volume shifted to electronic trading, and overnight volume increased ten-fold. Annualized return equals period return times 252, the number of trading days in a year.

These new stylized facts shed light on the mechanisms behind the market return and the equity risk premium. Obviously, the equity premium has been extensively studied and numerous theories have been proposed and tested. Most of them imply that expected market return should be proportional to risk. Market conditions vary drastically and systematically over a day. For example, average trading volume and volatility are particularly high during regular U.S. trading hours. Therefore, theories have distinct predictions about which parts of a day are particularly risky and thus should carry a higher premium. According to most theories, expected returns should be positive in all intraday intervals. However, market returns are insignificant outside the four-hour overnight period with low volatility. Thus, assuming average realized returns match expected returns, most theories struggle to explain high EU-open returns. Overall, this puzzle can shed light on how market returns are formed at the micro level.

Returns are not only high during EU-open, but the EU-open period is also less risky according to conventional measures. Realized volatility is 3.9 times lower during EU-open than during the rest of a day. Annualized Sharpe ratio is 1.66 compared to -0.05 for the rest of the day. Even though four hours constitute 18% of a trading day, EU-open contributed only 5% to daily return variance in 2004. This variance ratio gradually increased to 10% after 2008. Thus, EU-open's contribution to return variance is relatively stable. Also, EU-open returns are positively skewed, which makes this period even less risky, as many investors prefer positive skewness. In contrast, return skewness is negative during the rest of the day. Maximum daily loss and drawdown are only 4.5% and 8%, respectively, compared to 8.5% and 66.4% for the rest of the day. The only risk measure that is higher during EU-open is return kurtosis which is mostly due to much lower volatility. In sum, if anything EU-open appears less risky than the rest of the day, which deepens the return puzzle.

Market returns are computed as an average of realized returns from a single time series and thus are often sensitive to a given sample period. However, EU-open returns are extremely robust. A 7.6% annualized return is highly statistically significant with a *t*-statistic of 6.3. In contrast, cumulative return during the rest of the day is not significant (*t*-statistic of -0.2). Remarkably, EU-open returns are significant for every calendar year, calendar month, and weekday.[3] Not only are EU-open returns large and robust, but no other intraday interval comes

[3] Lowest annualized returns for year, month, and day-of-week are 2.25% in 2017, 3.11% in January, and 4.83% on Mondays, over the weekend, respectively.

close in terms of expected returns. 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 7:30pm, 7am, and 3pm. EU-open is the only statistically significant period if the moving window is extended to four hours. Overall, EU-open returns are remarkably robust while insignificant returns are observed for almost all other intraday intervals, which is an equally puzzling fact.

Few financial contracts are liquid outside of their regular trading hours. E-mini S&P futures are a rare exception. During a regular U.S. trading session, E-mini S&P is by far the most liquid index product especially for trading in size. However, it remains one of the most actively traded index contracts during Asian and European trading hours.[4] In a typical EU-open period, average trading volume is 14 billion dollars of S&P index exposure. Trading is active with almost two hundred trades per minute. Although the Asian trading session is least active, trading costs remain low during EU-open. The tick size is always binding for E-mini S&P futures. That is, the bid-ask spread is almost always one tick, including U.S. and Asian sessions, and is only 1.5 basis points on average. Market depth, the size available at the best bid and ask, is about 7.4 million dollars. These number prove that EU-open and Asian sessions are liquid: investors can trade in large size and take liquidity fast at low cost.

These results suggest a simple trading strategy to earn market returns: buy futures right before EU-open and close position after the period ends. U.S. investors can also participate by automating this strategy as E-mini futures are traded electronically. This strategy requires daily trading which incurs significant trading costs. However, despite frequent trading, this strategy remains profitable after costs. We assume investors pay the entire bid-ask spread, which allows immediate execution and is an upper bound on trading costs as one can reduce costs by providing liquidity. Limit orders fill within seconds. High market depth and volume facilitate execution of large trades. Assuming costs are equal to the bid-ask spread, the after-cost annualized average return, t-statistic, and Sharpe ratio are 3.2%, 2.6, and 0.7, respectively. Thus, costs reduce the profitability by slightly more than half, and returns remain significant. The baseline strategy can

[4] For example, CME Group (2017) estimates that E-mini S&P 500 futures are the 4th most actively traded equity index future in Asia with an average daily turnover of $7.1T during Asian session which is surpassed only by Hang Seng ($15.5T ADV), KOSPI 200 ($12T), and OSE Nikkei index futures ($8.2T). Of course, E-mini's trading volume increases five-fold once Asian session ends and European session starts.

be substantially improved by only trading when expected EU-open returns are high with ex-ante information. The conditional strategy relies on three ex-ante variables (VIX surprise, prior U.S. session returns, and Asian session volume) to predict EU-open returns with R^2 of 7.9%. The strategy only trades on half of days putting the same amount of capital in each trade. Per-day profitability doubles while costs remain the same. The conditional strategy has an annual cumulative return of 5.3% and Sharpe ratio of 1.4 after transaction costs. We estimate that the capacity of these strategies is several hundred million dollars. Long-term investors can also benefit from the EU-open anomaly by timing their trades. If a long-term investor wants to buy an E-mini future, then the best timing is before EU-open (or after EU-open for sells). Thus, investors benefit from high EU-open returns, while they are not compensated for holding market risk during the rest of the day. Overall, the EU-open puzzle appears profitable after conservative estimates of transaction costs.

After discovering the EU-open puzzle, we conducted several tests to explain it. First, Asian market close and European open are the only important recurrent events during this four-hour period. We use the change in daylight saving time as a natural experiment to disentangle the impact of Asia and Europe. Since Asia does not follow daylight saving time, Asian time shifts by one-hour relative to Europe for about half a calendar year. The run up in price during EU-open stays unchanged relative to European time and thus shifts in Asian time even though Asian closing times do not shift. Thus, the EU-open price run up stays in European and not Asian time, allowing us to conclude that Asian close does not drive the puzzle.

After establishing that high EU-open returns are triggered by European open rather than Asian close, we explore potential explanations for this effect including conventional price risks, investor sentiment, carry costs, news arrival, financial frictions such as inventory risk, and the uncertainty resolution. Some of these hypotheses, especially the uncertainty resolution, are helpful for explaining high EU-open returns. However, they struggle to explain why returns are zero during the rest of the day even though this 20-hour period is longer and arguably riskier.

The uncertainty resolution hypothesis comes closest to explaining the puzzle. By price uncertainty we mean that market prices deviate from fundamental value, an unobserved price that reflects all public information. Not all public information is fully processed. Price uncertainty can be quantified as a standard deviation (or distance) of the difference between price and fundamental value. High uncertainty leads to a price discount as an asset is riskier when its

price is further away from fundamental value. However, investors cannot tell whether it is overvalued or undervalued. Thus, investors require a price discount that is proportional to price uncertainty. Several theories formalize this argument and help us understand how the uncertainty resolution during EU-open can produce high returns. Hu, Pan, Wang, and Zhu (2019) argue that the uncertainty resolution leads to the pre-FOMC drift, and show in a stylized model that when uncertainty is resolved, prices increase but volatility can stay relatively low. 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." In their model, prices increase endogenously as information asymmetry is resolved around market open. As market price deviates from fundamental value, uninformed investors are only willing to buy the asset at a discount. Similarly, Easley and O'Hara (2004) study how the total amount of information in the market affects asset prices. They show that a lower fraction of informed traders makes the stock riskier for both informed and uninformed investors thus increasing expected returns. Expected returns increase because when information is private, rather than public, uninformed investors cannot infer information from prices, and consequently they require higher return. In these theories, the more information (through public or private signals) prices reflect, the smaller the price discount is relative to fundamental value.

During U.S. and European sessions, important investors are active and keep E-mini price close to the fair value. Hence, price uncertainty is low during most of the day, with the exception of the Asian session. Uncertainty can accumulate during Asian sessions as fewer investors are active and have limited capacity to process public information. The world's major investors are asleep and are thus absent from the market. Conversely, uncertainty is resolved during the EU-open. Large European investors return to the market and push E-mini prices towards fundamental value. European investors need not exploit private information; they can simply interpret public Asian news, including any price relevant information, not just macro news, independently from Asian investors.[5] Throughout the rest of the day, the price promptly reflects news as large investors are awake and active. Price uncertainty is due to the size gap between the Asian economy and its asset management industry. Indeed, Asia is the world's economic

[5] Even this assumption can be relaxed. All investors can be equally informed. Each investor observes an independent private signal about fundamental value. During Asian session, price reflects only Asian investors' signals while Europeans sleep. During EU-open, uncertainty is resolved as prices reflect all signals (from both Asian and European investors) thus making prices more informative.

powerhouse, yet few large investors operate in this time zone.[6] As such, investor's limited capacity to process information is only binding because the world's major investors live in cities like New York and London and value their sleep.

Several results are consistent with this hypothesis. First, the E-mini trade size is lowest during the Asian session and starts increasing through EU-open as large investors return to the market. Indeed, investor composition changes during EU-open. Second, EU-open returns should be increasing in price uncertainty accumulated overnight. Trading volume and realized volatility are high when information is released and thus reflect increased uncertainty. Indeed, EU-open returns are substantially higher following high volatility or volume during the Asian session. Third, a variance ratio test shows that prices are less informationally efficient during the Asian segment compared to the rest of the day. Specifically, daily returns based on pre-EU-open prices have higher variance than daily returns from post-EU-open prices, suggesting that pre-EU-open prices contain more noise.[7] The variance ratio steadily declines during EU-open. Forth, price uncertainty is often measured using changes in VIX (e.g., Hu, Pan, Wang, and Zhu, 2019). Indeed, EU-returns are higher after VIX is high relative to the weekly average. Finally, our main test relies on VIX future returns that reflect changes in uncertainty. Strikingly, VIX returns are positive through the Asian session, reflecting increased uncertainty. But the positive VIX trend stops as EU-open begins, and VIX returns start to decline before Europe opens. As such, EU-open VIX returns are highly negative. Uncertainty, as reflected by VIX future prices, rapidly declines during the second part of the EU-open, while cumulative market returns rapidly increase. Thus, patterns in market return and VIX futures return are consistent with the uncertainty resolution hypothesis. While these results are encouraging, it is less clear as to whether the uncertainty resolution can also explain zero return during the rest of the day.

We consider other potential explanations. Conventional risk-based theories attribute expected returns to higher risk as reflected by systematic volatility, price and volatility jumps, and negative skewness, among other measures. But these risk measures are lower during EU-open compared to the rest of the day. The peso problem can potentially explain the equity

[6] According to International Monetary Fund (2019), Asia contributes $31.6T to world's GDP, more than North America's and Europe's $24.4T and $21.8T, respectively. Thus, Asian news are important for world economy, but few large investors operate in this time zone and can fully interpret the news. Indeed, the 2017 survey shows that Asia's asset managers AUM is $4,58T, or 2.75 times lower than in Europe and 6.7 lower than in the U.S.

[7] Amihud and Mendelson (1987) introduce the variance ratio test and show that market volatility is greater during open-to-open versus close-to-close periods.

premium. However, it cannot explain why EU-open returns differ so much from returns in adjacent periods. EU-open is less risky compared to other intraday intervals but commands much larger risk premium. The 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 including several sentiment measures, including sentiment of U.S. and European retail investors, Baker and Wurgler's (2006) index, Michigan consumer confidence, and TED spread in the analysis, but EU-open returns do not depend on sentiment. Carry costs such as different interest, margin payments, and security lending fees are typically incurred after market close. Market return should be higher when these costs are incurred. We test this hypothesis even though these costs may or may not be higher during EU-open. Most carry costs increase in interest rates, but EU-open returns are uncorrelated with interest rates. Furthermore, carry costs are incurred every calendar day and thus are higher over weekends yet conversely, EU-open returns are slightly lower over weekends. Finally, it is likely that close-to-open stock returns are positive because most news arrive at night.[8] Indeed, market-moving U.S. news such as earnings announcements, analyst forecast revisions, and many macro announcements are released shortly before U.S. open or shortly after U.S. close. But EU-open occurs while the US is in deep night which is at least five hours away from these news intensive periods. Even European macro announcements are at or after the end of EU-open. Overall, news flow is low during EU-open.

We next consider inventory risk, which arises because liquidity providers are risk-averse and have limited capital. Dealers have to accommodate customer order flow, which causes them to hold suboptimal portfolios. Hence, they require a premium for holding this inventory risk, which is proportional to the size of an undesired position, asset volatility, dealer's risk aversion, and expected holding period (this idea goes back to at least Stoll, 1978).[9] Perhaps, some European investors fear night and avoid holding positions overnight by selling them at the U.S. close and buying them back at European open. Their price pressure would decrease prices around the close while also causing prices to rebound around the open. This pattern coincides with EU-open and thus could explain the EU-open price run up.

[8] See, Dan McCrum's article in Financial Times, on February 6, 2018.
[9] For example, Bessembinder (1992) shows that returns for some futures vary with the net holdings of hedgers, after controlling for systematic risk.

Inventory risk seems intuitive and plausible; however, on a closer look, this hypothesis faces numerous challenges. This theory's predictions simply do not line up with the data. First, hedging overnight risk requires daily trading, and trading costs add up quickly, making such hedging prohibitively expensive.[10] Second, if investors want to hedge overnight, waiting until EU-open is a waste of time. With an average hourly volume of 2.4 billion dollars during pre-EU-open, the Asian session can easily accommodate large trades. The bid-ask spread is always one tick. Third, if prices rebound so strongly around EU-open, then an equally large price drop should be around European or U.S close, but the data does not support this hypothesis. If anything, returns are more positive before U.S. close. Next, we ask the following question: why are investors so scared of the Asian trading session? The ten-hour period between U.S. close and European open represents only 10% of total return variance and contains fewer important news announcements than other periods. Leaving for a long lunch in the middle of the U.S. session carries almost the same amount of risk as sleeping though the entire Asian session. Why do dealers receive compensation only during EU-open but not during the rest of the night? This question is the biggest challenge for the inventory risk hypothesis because returns are slightly negative during the Asian session before EU-open; thus, dealers receive no compensation for holding inventory during these six hours, which contradicts inventory risk models. A free-rider investor, who carries no inventory risk at night, can earn the same return as the dealer by front-running and buying right before EU-open. As we show, this strategy is profitable after costs. Also, a free rider can further boost profits by buying at the bid as he loses nothing if a limit order remains unexecuted. Finally, any expected inventory change or order imbalance must be reflected in prices in advance. If European investors buy every morning, this would be known and their buying pressure would be reflected in prices hours before the open. Overall, most inventory and intermediary asset pricing models predict that the price should fall as dealers receive an inventory shock at the close. Price should then gradually increase until the open when dealers expect to unload their inventory imbalance. Thus, market return should be more positive during the entire Asian session to compensate dealers for inventory risk. However, returns are zero/negative in the data.

[10] Few investors can overcome this cost. High-frequency traders usually do not hold positions overnight, but they operate at a sub-second horizon and never hold large position during the day to begin with. Their effect on net positions is negligible.

We test the inventory risk hypothesis in several ways. First, inventory risk premium should be proportional to investor risk aversion, but EU-open does not depend on TED-spread, a popular measure of investor fear and limited capital. Second, as the Asian session became more active (trading costs decreased and volume increased ten-fold), inventory premium should decrease over time. However, EU-open returns did not change from 2004 to 2018. Finally, we look at a hypothetical. Suppose that the inability to trade at night matters. While investors can trade continuously during a regular overnight session, the E-mini market is closed for the weekend, from 4:15 pm on Friday to 6:00 pm on Sunday. Thus, according to inventory risk, EU-returns should be higher on weekends than on weekday nights, but EU-open returns are lower on weekends.

Figure 2 summarizes the return pattern implied by three main hypotheses. The graphs are stylized, but reflect the main pattern implied by each theory. In the baseline case, price increases linearly during the Asian session with constant positive return. Inventory risk implies that price drops as night-averse investors dump positions at the U.S. close and then price increases linearly until investors repurchase their positions at the open. According to the uncertainty resolution, price should underperform the baseline case as uncertainty increases through the Asian session. Then, price should surge/catch up to the baseline at the open as European investors reduce uncertainty and price converges to fundamental value. Returns are only positive during EU-open which is what the uncertainty resolution predicts.

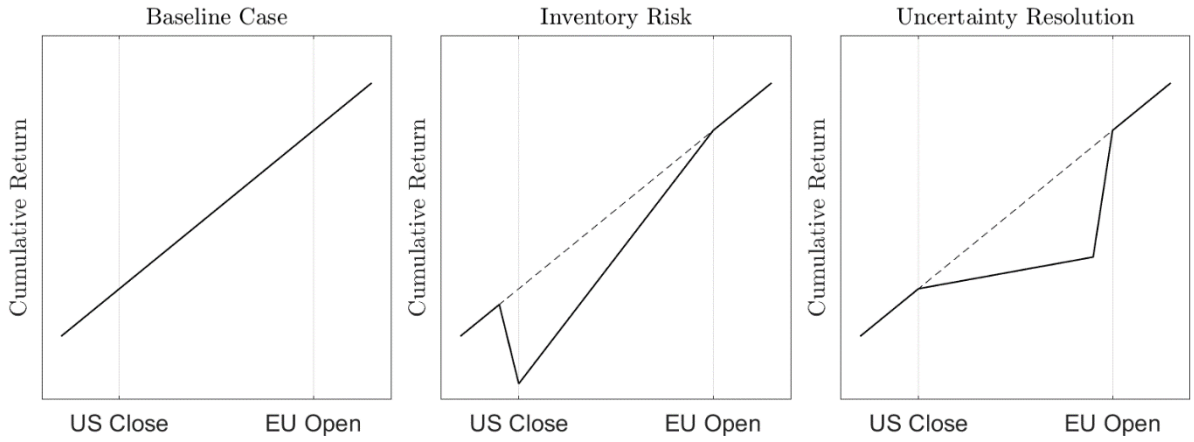


Figure 2. Cumulative market returns implied by three main theories. The equity premium is positive constant in the baseline case. For inventory risk, investors require high premium for every overnight hour. For uncertainty resolution, uncertainty discount increase overnight until prices revert to fundamental value at the open.

Our results about the time-of-day seasonality in market returns are related to several literatures. Stroud and Johannes (2014) study how E-mini S&P 500 return volatility depends on time of the day, but they are silent regarding average returns. The literature on day-night returns for individual stocks has a long history. Early evidence was mixed. Wood, McInish, and Ord (1985) report higher overnight returns for six months in 1971/72 while Rogalski (1984) and Harris (1986) find lower returns from 1974 to 1984 and from intraday data for 1983, respectively. Smirlock and Starks (1986) show that night returns in the DJIA are lower during the 1974-1983 period and are higher during 1963-1968 and 1968-1974. However, with bigger and better data, a clear pattern emerged. Cliff, Cooper, and Gulen (2008) find that the close-to-open period generates most of the daily return. They hypothesize that "price pressure effects from algorithm generated trading may account for some of the observed price patterns." Alternatively, Berkman, Koch, Tuttle, and Zhang (2012) argue that buying performed by attention-constrained investors drives up the opening price of stocks because of large fluctuations in the day prior which trigger retail investor attention. We identify a period during deep night that accounts for all positive overnight and daily returns and we propose an explanation.[11] Also, our results carry important implications for theoretical studies that attempt to explain returns around market closures (Slezak (1994), Longstaff (1995), Admati and Pfleiderer (1989), Foster and Viswanathan (1990), Hong and Wang (2000) among others). Our results are also related to other event-based anomalies for market return, the most prominent of which is the pre-FOMC drift.[12] We identify an equally strong and puzzling anomaly. Our results could be important for some of the theories explaining the pre-FOMC drift. Finally, Cornett, Schwarz, and Szakmary (1995), Ranaldo (2009), Breedon and Ranaldo (2013) and others study currency returns around

[11] A growing literature studies conditional properties of day-night returns. Heston, Korajczyk, and Sadka (2010) show that some stocks tend to perform systematically better than others during specific half hours of the trading day. Hendershott, Livdan, and Rösch (2018) study day-night CAPM. Stock returns are positively related to beta overnight but are negatively related to beta intraday. Bogousslavsky (2018) documents substantial variation in the cross-section of returns over day and night. Lou, Polk, and Skouras (2017) show that momentum profits accrue solely overnight. Several papers study day-night market return predictability. Akbas, Boehmer, Jiang, and Koch (2020) and Lou, Polk, and Skouras (2020) study how differences in opinion measured by overnight reversal predict future market returns. Gao, Han, Li, and Zhou (2018) show that overnight return for SPY ETF predicts its last half-hour return during regular trading. These studies focus on conditional returns and return cross-section, while we focus on average market return, the main component of the equity premium. Rapach and Zhou (2013) review the market return predictability literature. In concurrent work, Boyarchenko, Larsen, and Whelan (2020) study whether inventory risk can explain market return around London open and find that the returns are not significant after accounting for the bid-ask spread.

[12] Lucca, Moench (2015) and Boguth, Grégoire, and Martineau (2019) among others. Relatedly, Savor and Wilson (2013, 2014) show that market average are significantly higher on macroeconomic new announcement days.

the clock, a natural exercise as FX market is open 24/7 and has a unique market structure. The time-of-day return pattern for currencies differs greatly from the equity market.

This paper is organized as follows. Section 2 describes the data and methodology. Section 3 explores how market returns depend on time of the day. Section 4 explores after-cost performance of a trading strategy. Section 5 outlines and tests hypotheses that can potentially explain the puzzle. Section 6 concludes.

2. Data and methodology

Our main dataset includes one-minute trading bars for E-mini S&P 500 futures from TickData for the period beginning in 2004 and ending in 2018. Trading bars are standard and include open, high, low, and close prices as well as information regarding the number of trades and trading volume per minute. For the tests that require bid and ask prices (and sizes), we also use one-minute quoted prices data spanning 2010 to 2018. We focus on a front-month futures contract, which is determined by an industry standard roll-over rule implemented by TickData. Investors roll over their positions to the next month's contract as the front month contract expires. We exclude days when the market is closed, or the trading session is cut short due to a holiday. We first compute log returns, using the last price for every minute as the difference between log prices. Log returns can easily be aggregated to any required time horizon by simply adding them up. For easier interpretation, we often annualize average return by multiplying period return by the number of trading days in a year, which is usually 252.

For other variables, we compute the relative bid-ask spread as the difference between log bid and log ask prices. Market depth is measured as an average of the number of contracts available at the best bid and best ask. To compute dollar trading volume, we first compute dollar exposure for a single contract as the contract multiplier, $50, multiplied by the S&P 500 index level. For example, if S&P 500 is 1566, which is the sample average, then one E-mini S&P contract gives $78,300 worth of exposure. We can then multiply the number of contracts traded by the contract's dollar exposure to compute dollar volume. For volatility, we compute standard deviation for returns during a given period across all days, and then annualize it by multiplying by 252.

2.1 Institutional details on E-mini S&P and CME GLOBEX

We first explain some relevant details regarding the E-mini contract, including its trading environment and history. The Chicago Board of Trade (CBOT) introduced evening floor trading

in the late 1980s to address international demand for Treasury futures during non-U.S. daylight trading hours. However, the strain of trading into the night was more than many traders could handle. Thus, the Globex concept was conceived by CME Group in 1987 as a "low-impact" means of providing after-hours market coverage. The platform launched on June 25, 1992, running on the technology and network used by the wire service Reuters. It began with three currency products and one Treasury note product, but quickly expanded into other assets. Initial volumes were modest but interest was keen and the system grew steadily in popularity. The E-mini S&P 500 futures contract was introduced on September 9, 1997, after the value of the existing S&P contract became too large for many small traders. The contracts are referred to as "E-mini" because they are only 1/5 the size of normal S&P 500 contracts and are traded electronically on Globex. The CME Group instituted an open access policy for Globex in 2000, allowing customers to trade directly in the system, without having to go through a broker. As a result, business soared: In 2002, the Globex average daily volume exceeded one million contracts for the first time, and in 2004, the Globex volume exceeded physical pit volume for the first time. This is why we choose 2004 as a start of our sample period.

Currently, the E-mini contract trades 23.75 hours a day, 5 days a week, with the CME coming online on Sunday at 6:00 pm and closing again on Friday at 5:00 pm. Each afternoon, Monday through Thursday, there is a brief halt in trading from 4:15 pm to 4:30 pm.

Futures are popular in-part because of high embedded leverage and E-mini futures are not an exception. Traders can get into E-mini index futures for about 7% of the full cash value of the underlying stocks. For example, the full cash value of the E-mini is equal to the S&P 500 index price times the $50 multiplier. In other words, if the E-mini is trading at 3,000.00, the full cash value would be $150,000/contract (3,000.00 * $50.00). Therefore, a trader would be able to hold $150,000 worth of stock for only $11,000/contract (initial margin) or 7.3% of the full cash value.

The E-mini S&P is the most important contract on the S&P 500 index, which is a popular proxy for the market portfolio. Let us briefly compare it to other alternatives for getting S&P 500 exposure. First is the SPDR S&P 500 ETF. SPY is extremely popular. It was launched in 1993 and currently boasts $260B AUM. The E-mini S&P contract traded, on average, $142 billion in transaction dollar volume per day in 2012 versus the $18.5 billion that the SPY trades. SPY is only traded during normal and extended US exchange trading hours (6am-8pm EST). Regular S&P 500 futures were popular until late 1990s, but no one trades them currently. The E-mini

futures market leads the spot market. Other futures contracts such as E-mini Nasdaq 100 officially trade almost 24h but are extremely illiquid outside of U.S. trading hours.

3. Market return around the clock

In this section, we study how market return computed from prices of E-mini S&P 500 futures depend on the time of day. We discover a new stylized fact about average returns, which sheds light on how market return is formed at the micro level.

3.1 Trading regimes Throughout the Day: Asia, Europe, and the U.S.

Before focusing on returns, we explain how the trading environment changes through the day. A trading day informally consists of three regimes/time zones, Asia, Europe, and the U.S., which differ in investor composition and geography, trading activity, and liquidity. The trading technology stays exactly the same, as E-minis are only traded electronically and exclusively at GLOBEX. The Asian session is followed by the European and then the U.S. sessions with some overlap. A trading day starts at 6 pm when the CME GLOBEX system opens and ends at 4:15 pm the next day, when GLOBEX closes for a break. We refer to the period from 6:00 pm until Europe opens at 2 am as the Asian session. Japan opens at 7 pm followed by China and Hong Kong at 7:30. The countries remain open until 1 am, 2 am, and 3 am, respectively. Table 2 summarizes the trading hours for major markets. As expected, during the Asian session, most economic news concerns the Asian region and local investors account for most of the session's trading. The European session starts at 2 am (during Frankfurt and Eurex open) and ends when the U.S. stock market opens at 9:30am, although most European markets remain open until 11:30 am. London and several Euronext markets open at 3 am. The U.S. session starts at 9:30 am and ends at 4:15 pm, 15 minutes after the U.S. stock market closes. At 4:15 pm, GLOBEX closes for a short technical break, which marks the end of a trading day. After the break, a new day begins; however, most U.S. investors will have already left for the day.

These three regimes are characterized by drastically different market conditions that we study next. Table 3 describes trading activity and liquidity during the three sessions. As expected, these variables are lowest during the Asian session, higher during European hours, while the U.S. session is by far the most active. For example, volatility is 30% lower during the Asian session than during the European segment, which in turn is 50% lower than during the U.S. session. Thus, the entire Asian session only contributes 12% to total daily returns variance

and overall is not particularly risky. The difference between sessions is much larger for trading volume. Per-minute volume is 5.5 times lower during the Asian segment in comparison to the Europe session, and per-minute volume during the European session is 47 times lower than during the U.S. session. The gap between sessions is much wider for volume than for volatility, which can be interpreted as follows: the S&P 500 index value does depend on Asian economy, but Asian traders are much less important. This interpretation is supported by another measure of investor clientele: trade size. The average E-mini trade size is lowest during Asian hours (3.5 contracts). Compared to Asia, trade size is 43% higher during the European session and 132% higher during the US session Perhaps, investors who trade during the Asian session are smaller and less important.

Although the Asian segment is the least active session, it is still very liquid in absolute terms. In terms of volume, 36 million dollars are traded every minute or 17 billion dollars during the entire 8-hour Asian session. Thus, even large investors can easily execute large trades. On average, 121 trades are executed every minute. The Asian session is definitely active. The bid-ask spread almost always equals the tick size, which is set to $25. In relative terms, one tick corresponds to 0.015% (or 1.5 b.p.) as each E-mini S&P contract provides an exposure of the multiplier ($50) times the index level (average level of 1566 during our sample), which equals $78,300. Thus, the bid-ask spread does not vary across sessions, and as such is 1.56 b.p. during Asia. Because tick size is binding, significant volume accumulates at the best bid and ask, which is market depth. On average, 76 future contracts sit at the best bid with the same number sitting at the best ask, which equals about 6.5 million dollars available for immediate execution. Market depth is two times higher during Europe than during Asia.

3.2 Average returns around the clock

Figure 1 documents our main result by showing how log return for E-mini S&P futures accumulates throughout a day from 6 pm until 6 pm the next day, or over a 24-hour period. We annualize cumulative return to make the numbers easier to interpret.[13] It can also be interpreted as an average future price normalized to zero at the origin. Cumulative return remains flat and fluctuates between -1% and 1% p.a. throughout the overnight session. Vertical lines and arrows

[13] Every day, we normalize the starting price to one at 6 pm, when GLOBEX opens for overnight trading, and follow it until 6 pm the next day. We compute average log return for average minute across days, and then add up minute returns to compute minute-by-minute cumulative return.

on the figure mark the opening and closing times of important Asian and European markets (see Table 2 for the full list). Average price is slightly down (by 1.3%) by 11:30 pm, but then the trend changes. Cumulative return starts increasing slowly at first and then accelerates half an hour before European (Frankfurt, Amsterdam) open at 2 am. The price run-up stops shortly after London open at 3 am. During this remarkable period, cumulative return increases from -1.3% to 6.3% p.a. for a 7.6% total gain. After London open, cumulative return fluctuates between 2% and -2% during the European segment and most of the U.S. session. Surprisingly, volatility spikes at U.S. open and EU close have no effect on average return. The period around U.S. close is interesting. During the last two hours of the U.S. session, cumulative return increases by 4% p.a. This surge during U.S. close is economically large but not statistically significant (Figure 3) due to its huge volatility and volume. Strikingly, this pre-close price increase almost completely reverses between U.S. close at 4:15 pm and market re-open at 6 pm, which sees a return of -2.8%.[14]

Overall, more than 100% of the average market return is concentrated in four hours: between 11:30 pm and 3:30 am EST. We call this price run-up period "EU-open" because 11:30 pm corresponds to 4:30 am German Time, when the first European investors wake up and check the market. Return upward-trend accelerates around 1:30 am (7:30 am in Europe) when many traders arrive to the office half an hour before the start of the European session. Returns continue to increase as London investors check-in. The second half of EU-open accounts for 5.4% of the total return of 7.6% due to main European markets opening during this time. It is remarkable how steadily returns increase during EU-open without zigzags.

Figure 3 explores the statistical significance of cumulative returns during EU open, US close, and the two periods in between by showing confidence intervals around average cumulative returns minute-by-minute. Of course, the confidence bounds widen with time as volatility accumulates. EU open cumulative return becomes statistically significant 40 minutes into the period 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 and become insignificant.

Table 1 provides a comprehensive set of statistics for EU-open return and for the rest of the day. Average EU-open return is 7.60% p.a. with a t-statistic of 6.35, while return during the rest of the day is -0.8% with a t-statistic of -0.17, which is virtually zero. The EU open period is

[14] The market is closed between 4:15pm and 6pm, hence we connect the two prices with a straight line in Figure 1.

also less risky according to conventional risk measures. First, its annualized volatility is 4.55%, or 3.9 times lower than the rest of the day. Skewness is positive (1.64), meaning 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) alongside total daily return (-0.42). The largest daily loss is -4.52% for EU-open and -8.47% for the rest of the day. A trading strategy based on EU-open has a maximum drawdown of 8%, while drawdown is 66.4% for the rest of the day during the financial crisis. Kurtosis is the only measure showing EU open is riskier, with 57 during the European session versus 16 for the rest of the day. Forth return moments are the same, but EU open has much lower volatility while kurtosis is proportional to the ratio of the two. This means that EU open is usually quiet but occasionally experiences large price moves. Interestingly, median returns are proportional to time: 2 b.p. (4.7% p.a.) for EU-open and 6 b.p. for the rest of the day. However, skewness plays a major role in determining average returns. In sum, if anything, EU open appears less risky than the rest of the day, which deepens the return puzzle.

Cumulative returns figures provide visual evidence about which parts of the day are important. We complement them with a moving average analysis that can discover more granular average return patterns. The idea is simple. Estimate average return and its t-statistic over a one-hour window, then move the window by one minute and repeat. Panel A of Figure 4 shows the resulting centered moving-average *t*-statistics over the day. For the negative return zone, the t-statistic touches 5% significance threshold in the hour right before EU open and in a short period when U.S. macro news are released at 9 am. For positive returns, the moving window t-statistic for average returns reaches six during EU open while only two other hourly intervals briefly touch a 1% significance threshold: around 7:30 pm and 7 am. The U.S. session around 3 pm crosses the 5% level but does not reach 1% significance. This figure clearly shows that EU open stands out massively even during a relatively short time period, like one hour in this case. If the window is extended to a longer period such as four hours in Panel B, EU open remains the only statistically significant period with a t-statistic greater than six.

For the rest of the paper, we focus on EU open returns. We assume that expected market return is computed as an average of realized returns. This estimate is often sample-dependent due to high return volatility and time variation in expected returns. Strikingly, EU returns are extremely robust and consistent. Table 4 reports EU open returns by year and compares them to

the rest of the day. The lowest EU returns are 2.25% p.a. and 4.53% in 2017 and 2004, respectively. The highest EU-returns are 16.24% and 13.52% in 2009 and 2015. Thus, returns are positive and economically significant every year. EU open returns during the first and the second part of the sample match almost exactly. EU open return volatility follows trends in the overall market volatility, and is highest in 2008 while at its lowest in 2017. On the other hand, returns during the rest of the day vary a lot. Returns during the rest of the day are statistically significant in only one year (15.8% with t-stat of 2.5 in 2017); in contrast, EU open return is statistically significant in nine out of fifteen years.

The lowest return for the rest of the day is, as expected, during 2008 (-55.8%); in contrast, EU open return is 9.8% in 2008. Figure 6 supplements this table by showing cumulative return and the corresponding t-statistic for a two-year moving average over the sample period. EU open returns are positive and statistically significant in almost any two-year window. The financial crisis does not affect them apart from higher volatility. In contrast, return for the rest of the day is never significant except for two instances when it touches a 5%-significance level in 2014. Thus, average market return is almost never significant outside EU open, which is almost as incredible as the consistently high EU open returns.

Finally, Table 5 reports how EU open returns depend on the calendar month and day of the week. EU return is highest on Tuesdays (9.64%) and lowest on Mondays (4.83%), which corresponds to the weekend. January and October have the lowest EU-open return at 3.11% and 3.75%, respectively. Return is highest in December and February (11.96% and 11.49%). EU-open return volatility is similar during all weekdays and calendar months with the exception of higher volatility in October due to financial crisis. Overall, EU-open returns are consistently positive and do not seem to vary systematically.

3.3 Volume, volatility, and liquidity around the clock

We focus on average market return, but other market variables including volatility, volume, the bid-ask spread, and market depth have interesting patterns around the clock as well. Figure 5 shows how these four variables depend on the time of the 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, U.S. macro announcements are important. They correspond to the two biggest (one-minute) volatility

spikes; however, the spikes quickly revert to a normal volatility level. Volume spikes during these two episodes are much less pronounced. Perhaps macro news move prices but do not trigger large portfolio rebalancing. Market depth decreases while the bid-ask spread increases. It is likely that liquidity providers avoid announcement uncertainty. Even though the two minutes of a day that correspond to U.S. macro news have high volume and volatility, average returns are not significantly different from zero during these periods.

Second, volatility and volume have a U-shaped pattern during the U.S. session and pre-US European session. Volume is U-shaped during the US session. It is largest at 4 pm then drops during the last 15 minutes; however, it still remains high. The Asian session's volatility and volume pattern differs. Volume and volatility spike at Hong Kong/China open and then gradual 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 make volatility and volume permanently higher than in pre-period. Third, volatility and volume spike at 6 pm when GLOBEX re-opens after a technical break and investors trade on the information accumulated during the break. Finally, both measures typically spike at every round-numbered half-hour partly due to news broadcasts, but mostly due to investor preference for round numbers.

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 evidently related to volatility and volume but also have interesting individual patterns. Market depth increases exponentially in the period approaching the U.S. session, reaching levels that are three times higher than during the rest of the U.S. 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 huge spikes during US macro announcements.

4. Trading strategy

In this section, we explore the after-cost profitability of a strategy that buys E-mini futures before EU open and closes the position at the period's end. This strategy requires trading every day and thus accumulates significant trading costs. Proper estimates of trading costs are essential for this analysis. We estimate costs conservatively by assuming that investors pay the entire bid-ask spread: half-spread to get in and the other half-spread to close the position. We estimate bid and ask prices from trades. This is relatively easy as the bid-ask spread is almost always one tick, and many trades execute at bid and ask every instance. 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 (The TickData database provides quotes starting from 2010). We prefer the trade-based bid and ask prices because they rely on actual trades and are available for the entire sample period.

We report results for this baseline strategy with and without trading costs in Table 6. Before costs, the stratey makes a 7.6% annualized return with a Sharpe ratio of 1.65, which of course matches returns in Table 1. After costs, the profitability declines as expected, as daily trading is costly. Expected return declines to 3.2% and the Sharpe ratio declines to 0.69. Thus, trading costs reduce profitability by 58%. The return remains statistically significant with a t-statistic of 2.6, and the Sharpe ratio is high. This baseline strategy provides an upper bound on the after-cost profitability.

This baseline strategy can be improved.[15] Instead of trading every day, investors could trade only on days with ex-ante higher expected returns (we call this "conditional strategy"). We introduce a simple conditional strategy that trades on half of all days and puts equal capital in each trade. We identify days with high expected EU returns in two steps. First, we regress EU open returns on three ex-ante predictors (known prior to EU open). EU return is higher when the prior US return is low, VIX is high relative to weekly average, and volume is high during the Asian session before EU open. The return predictability is strong with an in-sample R^2 of 7.9% and a slightly lower out-of-sample R^2. To put this number in perspective, Gao, Han, Li, and Zhou (2013) predict intraday returns for SPY ETF and find an R^2 of 2.6%, "a level that exceeds

[15] For example, instead of requesting immediate execution and paying the spread, investors can reduce costs by providing liquidity. Almost two hundred trades per minute during EU-open encourage liquidity provision. Most of EU-open return is concentrated in the second two hours, thus investors have ample time to accumulate positions.

typical predictive R^2 s at the monthly frequency." After estimating the predictive regression, we pick half of the days with the highest expected return from this model. Conditional strategy only trades on these days and puts equal amounts of capital in each trade. This approach reduces overfitting as it (i) considers only three predictors, (ii) picks 50% of the days for trading, and (iii) puts equal capital in each day. Performance can be further improved by optimizing these dimensions. Our point is simply to show how the baseline strategy, which is already profitable after-costs, can be easily improved using prior information.

Table 6 shows that conditional strategy is almost as profitable as the baseline strategy which trades every day. Cumulative annual return for the conditional strategy is 7.44% before costs while the baseline strategy's return equals 7.56%, despite trading on only half the days. Thus, the days that conditional strategy skips have close to zero EU return (0.12% annualized). The bid-ask spread is almost always one tick, so the per-trade costs do not change. However, conditional strategy reduces cumulative trading costs by only trading on half of all days. An alternative interpretation is that conditional strategy picks days with double average (per day) return, while trading costs are similar for all other days. After-cost expected return is 5.3% with a t-statistic of 5.3. Its Sharpe ratio is 1.39, which is close to the pre-cost Sharpe ratio for the baseline strategy (1.65). To sum up, the conditional strategy performs extremely well.

How much capital can be put into these strategies? How do returns convert into dollar profits? Account level data regarding how large investors trade is necessary to properly answer these questions. However, even the public data that we have can provide useful insights. Practitioners estimate that good execution algorithms can trade about 10% of the average total volume without price impact.[16] Buying more than 10% would incur price impact. We rely on this estimate to compute the strategy's capacity. A strategy buys 10% of observed trading volume during each minute for a two-and-a-half hour period beginning 30 minutes prior and ending two hours into EU open. The later threshold is feasible because most EU returns are realized in the second half (last two hours). This strategy is akin to a standard VWAP algorithm. Futures are bought at the ask minute-by-minute, which is conservative as standard algorithms can establish positions up to 10% of total volume while paying less than half-spread in costs. The two-and-a-half hour acquisition window can be potentially extended to include more of the Asian session. Similarly, we close the position by trading minute-by-minute at the bid and executing 10% of

[16] E.g., ITG (2015) and MSCI (2019) "Liquidity Metrics" report.

volume starting from the end of EU open. High volume during the European session accelerates the liquidation which usually is completed within one hour. Subject to its assumptions, this strategy can be used to estimate trade capacity. On a typical day, position size is 600 million dollars. For the baseline strategy, annual profits of 45 and 19 million dollars are produced with and without costs (traded at midquote versus buy at the ask and sell at the bid), respectively. For the conditional strategy, the pre and post-cost profits are 54 and 32 million dollars per year. Of course, these estimates require strong assumptions about the price impact of current and additional volume, but they provide a useful starting point. Overall, the strategies produce economically significant profits after trading costs.

Even long-term investors can benefit from high EU returns. Obviously, they cannot utilize the high-turnover daily buy/sell strategy. However, the EU-open puzzle should affect the timing of their trades. If a long-term investor wants to buy or sell a future, the time period before or after EU open will be the most optimal. This way investors benefit from high EU open return as they are not compensated for holding market risk during the rest of the day.

Overall, even with conservative estimates of trading costs, the EU-open strategy remains highly profitable. The strategy's return declines by slightly more than half but remains significant. A simple conditional strategy keeps cumulative return the same while cutting costs in half by trading on only half of all days. Its already impressive performance can be further improved by (i) sizing trades proportionally to expected return and (ii) minimizing trading costs by providing liquidity. Both baseline and conditional strategies have a hundred-million-dollar capacity.

5. Explaining the puzzle

In this section, we consider several explanations for the EU-open puzzle. We first outline the returns patterns implied by the explanations. Conventional risk theories imply that expected returns should be proportional to risk and thus positive in all intraday subperiods. Perhaps, expected return is constant and positive in calendar time or in volatility time (which corresponds constant Sharpe ratio). This is a baseline case to compare other theories against. We focus on two most promising hypotheses: inventory risk and uncertainty resolution. Figure 2 summarizes return patterns implied by three main hypotheses. In the baseline case (Panel A), the price increases linearly during Asian trading session, i.e., constant positive return. Inventory risk

implies that the price drop as night-averse investors dump their positions at the U.S. close and then price increases linearly until investors repurchase their positions at the open (Panel B). According to uncertainty resolution (Panel C), price should underperform the baseline case as uncertainty increases through the Asian session, and then the price increases/catches up at the open as European investors reduce uncertainty by aligning price with fundamental value. Uncertainty resolution generates return pattern which is closest to the data.

5.1 Asian close versus European open

To understand why EU-open returns are high, we first disentangle the impact of two major recurrent events during this period: European markets open (Frankfurt and then London) and Asian markets close. Intuitively, Asian session is less active, and thus Asian close is less likely to affect EU-open returns. This conclusion is difficult to confirm because China closes at 2 am exactly when Frankfurt opens. Similarly, London opens and Hong Kong closes at 3 am. Table 2 summarizes open and closing times for major equity markets. We separate the effects of Asian close and European open by using daylight saving time (DST) as an exogenous shock to relative time between Europe and Asia. Asia does not have DST, while Europe and the U.S. do. DST in US extends from the second Sunday in March to the first Sunday in in November. DST in Europe extends from the last Sunday in March to the last Sunday in October. Thus, DST in Europe and the U.S. overlap except for a brief four-week period.

Thus, from the US perspective, Hong Kong market closes at 3am EST in winter but at 2 am in summer.[17] If Asia is important, the EU-open price run-up will shift with the shift in Asian time relative to Europe/U.S. Figure 8 tests this hypothesis by comparing cumulative returns and trading volume around EU-open during winter and summer DST periods in Europe. In European time, cumulative returns and volume are remarkably similar for the two subperiods. Thus, the EU return pattern is constant in European time and thus shifts in Asian time. Indeed, if the same graphs are presented in Asian time in the lower two panels of Figure 8, a one-hour shift between summer and winter return (and volume) patterns emerges. The fact that volume pattern "lives" in European time is not surprising as European session is more liquid than Asian session. This shift

[17] Also, Asian exchanges open one hour later when US DST is active. For example, Tokyo Stock Exchange opens at 18:00 when DST is not active (winter time) and at 19:00 when DST is active (summer time). Note that DST in US always includes DST in Europe. The former starts 2 or 3 weeks earlier (the second Sunday in March versus the last Sunday in March) and ends 1 week later (the first Sunday in November versus the last Sunday in October). There is a four-week period (three weeks in March and one week in November) when US switched to DST while Europe not, but we do not use it in our test.

in the cumulative return confirms that European open and not Asian close drives the EU-open price run up.

5.2 Uncertainty resolution and VIX

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

Because uncertainty resolution is less well-known than inventory risk, we first explain this mechanism and then apply it to the EU-open puzzle. By price uncertainty we mean that market prices deviate from fundamental value, the unobserved prices that would reflect all public information. Fundamental value is properly risk-adjusted with CAPM or a multi-factor model. It is not surprising that prices can deviate from fundamental value as processing public information is difficult and costly. Investors cannot fully process information. E.g., an annual report contains an ocean of price-moving information that often is difficult to interpret. By analogy, physics laws imply that an engine cannot transform energy into useful work at 100% efficiency. Also, investors can differ in their processing ability and capacity. Price uncertainty can be quantified as a standard deviation (or distance between) of the difference between fundamental value and market price. Thus, price can randomly deviate from fundamental value while the average difference is zero. Uncertainty measures how far price can be from the value.

Uncertainty is priced because investors rely on prices to choose their portfolios and make other investment decisions. Higher uncertainty makes an asset riskier as its price is further away from fundamental value but investors cannot tell whether the asset is overvalued or undervalued. Thus, investors will require a price discount that is proportional to price uncertainty. Hu, Pan, Wang, and Zhu (2019) formalize the above intuition with a stylized model. In their three-period model, final payoff *D* is paid in the last period and has variance σ_D^2. The variance is random and its realization is revealed in the second period, hence uncertainty resolution. They show that when uncertainty is being resolved not only prices are increasing but volatility can stay relatively low. 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 consequently they require higher return. In both

theories, the more information (through public or private signals) prices reflect the smaller is the price discount relative to fundamental value. These related theories help us understand how uncertainty resolution around EU-open can produce observed returns. If investors know that important information exists but is withheld from the market, prices will be lower to reflect the risk that the information will move the price when it finally becomes public directly or indirectly through informed trading. Realized volatility is not necessarily much higher when uncertainty is high, e.g. a stock of a company that expects to hear form FDA on its drug approval.

During U.S. and European sessions, many smart investors are active and keep prices reasonably close to fundamental value. However, uncertainty can accumulate during the Asian session as fewer investors are active and they can differ in their ability to interpret public information. We argue that price uncertainty is low during most of the day as any new information is immediately incorporated into the E-mini price, but the Asian session is an exception. Price uncertainty increases through Asian trading hours as investors cannot fully process public information. The most informed investors quit the market during Asian session as they have to sleep. Uncertainty is resolved during the EU-open. Large European investors arrive to the market and push E-mini price towards the fair level. European investors do not necessarily have private information; they just better interpret public news from Asian session, which include any price relevant information not just macro news.

Indeed, there is a gap between Asia's contribution to the world's economy and its asset management industry. Asia is world's economic powerhouse. Asian news are important for world economy, but few large investors operate in this time zone and can fully interpret the news. Thus, prices can deviate from fundamentals until European investors wake up and correct them. During the rest of the day, the price promptly reflects news as large investors are awake and active. Price uncertainty is due to the size gap between Asian economy and its asset management industry. Consistent with this hypothesis, we find that trade size is lowest during Asian session, and it start increasing at the start and through EU-open as large investors return to the market. Of course, the information friction that we found is large only because many important investors live in cities like New York and London and value their sleep.

Several results are consistent with the uncertainty resolution explanation. First, last panel in Figure 5 shows that trade size starts increasing right at the start of EU-open and keeps increasing through the period indicating that EU-open is indeed the time when European

investors indeed return to the market after night break. Second, EU-open return should increase proportional to price uncertainty. Trading volume and realized volatility reflect how much public information is released and thus are proportional to price uncertainty during Asian trading hours. As predicted by the hypothesis, EU-open returns are substantially higher when volatility or volume are high during Asian session before EU-open but are unrelated to the preceding U.S. volatility or volume after controlling for Asian volatility as Table 7 shows. Third, prices are less efficient during Asian session compared to the rest of the day. A variance ratio test shows that prices are less efficient before EU-open compared to after-EU-open as Figure 11 shows. Specifically, daily returns based on pre-EU-open prices have higher variance than daily returns from post-EU-open prices by about 5% (in relative terms), suggesting that pre-EU-open prices contain more noise.[18]

Finally, our most direct evidence in support of uncertainty resolution hypothesis comes from VIX index and VIX futures. VIX is commonly used to measure uncertainty. For example, Ederington and Lee (1996) and Beber and Brandt (2006) show that the uncertainty measured by implied volatility from options on Treasuries drops substantially after the release of macroeconomic news. Hu, Pan, Wang, and Zhu (2019) use VIX and positive shocks to VIX to study uncertainty resolution around FOMC announcements. We first show that when uncertainty is high, as measured by VIX (at prior U.S. close) or its value relative to weekly average, EU-open return is more positive. Table 7 reports how EU-open returns depend on VIX level at the previous U.S. close and its shock relative to weekly average in univariate regressions. VIX level and shock have t-statistics of 2.4 and 4.0 respectively, and they become even more significant after other controls are included.

Ideally, we would like to see how VIX changes during Asian session and EU-open. Unfortunately, VIX is computed from S&P 500 index option prices, that do not trade during EU-open. To get around this problem, we use VIX futures, the only VIX-linked product that actively trades during the period of interest. VIX future are cash settled into spot VIX at maturity. VIX futures were introduced by CBOE Futures Exchange (CFE) on March 26, 2004, but average

[18] Finally, we conduct a case study based on the U.S. 2016 presidential election. An unexpected victory for Donald Trump made the markets tumble with E-mini futures down 5% by 10 pm when the winner became apparent. Figure 14 shows that E-mini rebounded between midnight and 4 am, which almost exactly coincides with the EU-open period. The price apparently overreacted during Asian session and was corrected during EU-open. Overall, these results are encouraging but it remains an open question whether zero return during the rest of the day can be explained by the uncertainty resolution hypothesis.

daily volume only crossed 10,000 mark in 2010 and surpassed 300,000 contracts in 2017. On June 22, 2014, VIX futures trading hours were finally extended to match E-mini futures, or nearly 24 hours a day. Thus, VIX futures trading covered Asian and EU-open periods only for 3.5 years. Figure 12 shows how VIX futures returns depend on time of day during this sample period. We follow exactly the same methodology as for E-mini futures. Strikingly, VIX returns are positive during the pre-EU-open part of Asian session, cumulative return is 10% annualized. Cumulative return increases at constant rate except for the drop from 3% to 0% during China/Hong Kong open at 8pm EST. This result is consistent with uncertainty building up during the overnight session (positive VIX return) and that market open indeed reduce uncertainty (Asia open VIX drop). During EU-open, cumulative VIX return start decreasing and quickly become negative. Cumulative VIX return is -15% during EU-open, and it closely follows market return with the opposite sign. Thus, uncertainty decreases during EU-open and especially its second part then European markets officially open. This is a direct prediction of the uncertainty resolution hypothesis. VIX return varies widely but is not statistically significant during the rest of the day, which is consistent with uncertainty being relatively stable during this period. The bottom panel of Figure 12 shows how EU-open VIX return are consistently negative and have low volatility over 2014 to 2018 sample period. In contrast, return during the rest of the day is much smaller in magnitude and more volatile.

5.3 Inventory risk

What if many investors are averse to the overnight period and avoid it by hedging or not carrying positions during the Asian session? If so, such investors have to pay a premium to liquidity providers, who take this risk. Inventory risk (or intermediary capital) arises because liquidity providers are risk-averse and have limited capital. Dealers are required to accommodate customer order flow, which makes them hold suboptimal portfolios. Hence, they require premium/compensation for holding this inventory risk, which is proportional to the size of undesired position, asset volatility, dealer's risk aversion, and expected holding period. Perhaps, some European investors fear night and avoid holding positions overnight by selling at the U.S. close and reestablishing their positions at the open. Alternatively, investors can hedge their equity positions by selling E-mini futures overnight and thus keep zero beta during the undesirable period. Intuitively, their price pressure would decrease prices around the close until prices rebound around the open. This price rebound can coincide with EU-open. Thus, inventory

risk hypothesis argues that EU-open returns are high because night-averse investors re-open their positions round European open and their order flow pushes prices higher.

Inventory risk seems intuitive and plausible; however, on a closer look, this hypothesis faces numerous challenges in explaining EU-open returns. The pattern implied by the theory just does not line up with the data. We carefully evaluate each implication of inventory risk hypothesis one-by-one. First, hedging overnight risk requires daily trading, and trading costs quickly add up and make such hedging prohibitively expensive. The bid-ask spread is 1.56 bps on average while the entire daily market return is 3.8 bps, thus the spread consumes almost half of the return. Commissions and price impact further increase the costs.

Maybe inventory risk is priced because Asian session is highly illiquid, and investors must wait until European open to adjust their position. If investors want to adjust positions, then waiting until EU-open is a waste of time. With an average volume of 2.4 billion dollars per hour (pre-EU-open), Asian session is certainly liquid enough to accommodate large trades. Waiting until EU-open does not reduce trading costs as the bid-ask spread is always one tick regardless of time of day. E-mini market is fully electronic and trade execution can be easily automated either in-house or using broker-supplied algorithms that are available even to retail investors.

We directly test whether the inability to trade during Asian session or its perceived illiquidity affect cumulative returns during Asia and EU-open. First, while investors can trade continuously during a regular overnight session, the E-mini market is closed for most of the weekend: from 4:15pm on Friday to 6:00pm on Sunday. Thus, 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 compared to weekends. Trading volume is essentially identical for the two samples except for high volume during the first hour of weekend trading when information accumulated from Friday close to Sunday open is being priced. Trajectories for cumulative returns are also remarkably similar. Weekend returns are noisier because the sample size is four times smaller than for weekdays. For weekends, cumulative return increases from 0.4% to 5.6% during the EU-open, while it increases from -1.6% to 6.6% for weekdays. Thus, if anything weekend returns are lower than on other days, and the difference is marginally significant (t-statistic of 2.3). The results of this test are not consistent with the hypothesis that non-trading periods carry higher premium.

Next, we test whether night illiquidity leads to high inventory risk premium by comparing the first and second parts of the sample as liquidity during Asian session increased substantially. Figure 10 shows that while trading volume remained unchanged during the U.S. session, it doubled during European session and quadrupled during Asian session. Overnight liquidity clearly improved. However, cumulative returns are identical though the entire trading day until the U.S. open. Returns diverge during the U.S. session due to the financial crisis in the per-2011 period. Thus, night liquidity does not affect EU-open return even though it should according to the inventory risk hypothesis.

Why do investors are so scared of the overnight period and specifically Asian session? Not clear as this session is least risky (compared to Europe and the U.S.) as measured by conventional measures. Ten hours between the U.S. close and European open represent only one-tenth of total return variance and contains fewer important news than other periods. Leaving for a long lunch in the middle of the U.S. trading session is almost as risky as the entire Asian session. Figure A.1 in the Appendix confirms this point by showing cumulative return in calendar time and in variance time. The Asian period before EU-open contributes 10% to the variance, EU-open contributes another 8%. In contrast, a seven-hour U.S. trading day contributes 60%.

If prices rebound so strongly around EU-open, then an equally large price drop should be around European or U.S close, but we do not see it in Figures 1, 3 and 4. If anything returns are more positive around U.S. close, and cumulative return for the day increases from 6% to 10% between 2pm and 4:15pm, when the U.S. market closes. Returns are highly volatile during this period.[19]

A more fundamental challenge is why dealers receive compensation only during EU-open but not during the rest of the night (Asian session before EU-open), which contradicts inventory models. Not only dealers are not compensated for holding inventory overnight, they lose money as cumulative return is slightly negative (-1.5% p.a.) in the pre-EU-open period. Maybe dealers are compensated at EU-open, but a free-rider investor (who carries no inventory risk) can earn the same EU-open return by "cutting the line" and buying right before EU-open. We show in Section 4 that this strategy is profitable after costs. The free rider can boost returns by buying at the bid as he loses nothing if the limit order is not executed.

[19] In the extended sample, we find that returns are massively negative around the U.S. open during the burst of the dot-com bubble in 2001-2002. We attribute these returns to margin selling by the U.S. investors.

Finally, any expected inventory change/order imbalance must be reflected in prices in advance. If European investors buy every morning at the open, this would be known, and their buying anticipated pressure would be reflected in prices hours before the open. Similarly, only unexpected selling lowers prices. The observed return pattern with high EU-open return and no significant corresponding drop in price is consistent with EU-open buying pressure being unexpected and corresponding selling being anticipated.

Additional tests show mixed results. First, compensation for inventory risk should be proportional to expected volatility, EU-open returns are indeed increasing in VIX level and its innovations. But the uncertainty resolution hypothesis has a similar prediction. Second, EU-open returns do not depend on TED spread, which is a popular measure of investor fear/risk aversion and limited capital.

Overall, most inventory (or intermediary asset pricing) models predict that the price should fall as dealers receive an inventory shock at the close, the price then should gradually increase until the open as dealers expect to unload inventory imbalance at the open. Thus, market return should be higher (more positive) during the entire Asian session to compensate dealers for holding inventory risk. This predicted return pattern is completely different from the one observed in the data. In Figure 1, price remains flat or decrease slightly during Asian session and then increases rapidly during EU-open.

5.4 Carry costs and sentiment

Conventional risk-based theories attribute expected returns to higher risk as reflected by systematic volatility, price jumps, negative skewness, among other measures. But all of these risk measures are lower during EU-open compared to the rest of the day. Also, EU-open does not contain important macro news. European macro announcements are at or after 3:30 am, which is the end of EU-open. The peso problem is a popular explanation for why equity premium is so high. However, it cannot explain why returns in adjacent periods differ from EU-open so much. That is, EU-open is less risky than other intraday intervals but commands much a larger premium.

A 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. We consider four sentiment measures: the bull-bear sentiment from the AAII investor survey (proxy for the sentiment of U.S. retail

investor), the Sentix Investor Confidence Index (proxy for European investor sentiment), Baker and Wurgler (2006) index (proxy for institutional investor sentiment), the University of Michigan consumer confidence, and the TED spread (difference between LIBOR and Treasury rates). None of them significantly predict EU-open returns except for Michigan consumer sentiment that is significant in some specifications.

Carry costs including different interest/margin payments and security lending fees are typically incurred after market close. Market return should be higher during the night period when these costs are incurred to compensate investors for the costs. It is not clear that any of these costs are concentrated in EU-open, but we still test this hypothesis. Carry costs are usually proportional to the level of interest rates, but EU-open returns are uncorrelated with 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. Thus, we conclude that sentiment and direct carry costs are unlikely to explain the EU-open puzzle.

6. Conclusion

In this paper, we introduce a new puzzle about average excess market return. E-mini S&P futures are actively traded almost 24/7, and we use their prices to study how excess return for S&P 500 index depend on time of the day. One period clearly stands out. All of average market return is concentrated in just four hours between 11:30pm and 3:30am EST, which corresponds to deep night in the U.S. and early morning in Europe. Return is particularly high in the second half of this period, when European markets start to open. The EU-open return is highly statistically significant, and the price steadily increases during this period. In contrast, average return during any other four-hour period is zero or slightly negative. EU-open has low risk according to conventional measures. High return combined with low risk results in an impressive Sharpe ratio. The EU-open return pattern is extremely robust and is observed in every year, every calendar month, and day-of-week. We also show that a strategy of buying/selling futures before/after EU-open is profitable after accounting for conservative estimates of trading costs and has high trade 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 European open rather than Asian close.

We propose and test several potential explanations. One of them, uncertainty resolution, is particularly promising. As new information arrives to the market, investors quickly process it and update prices through trading. Thus, prices are normally close to fundamental value. However, during Asian session, a critical group of investors sleeps and thus does not participate in information processing. As a result, information uncertainty accumulates through Asian session as prices can further deviate from fundamental value because incoming information is not fully processed. As European investors wake up and process the accumulated information, uncertainty is resolved, and prices increase. Several tests, most notably VIX futures returns, support this theory.

Taken at face value, these results imply that uncertainty resolution arises naturally in financial markets and is a critical determinant of the average market return. Thus, a natural next step would be to study the relation between average returns and uncertainty in other contexts. Overall, information uncertainty could play a more prominent role in asset pricing than is currently assumed.

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Table 1
Returns during EU-open and the rest of the day
This table reports essential 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). E.g., average return during EU-open is 7.42% annualized. We also report return distribution percentiles, that are not annualized (e.g., minimum return during EU-open is -3.97%). The entire trading day (last column) is split into EU-open (from 11:30 pm to 3:30 am EST) and the rest of the day (6 pm to 11:30 pm and 3:30 am to 4:15 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 including 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, %	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 as well as EST. 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 EST: Moscow, Johannesburg, Tel-Aviv, Saudi, Bursa Istanbul, and at 9:30 EST: 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)	9:00–15:30	3:00–11:30	None	Mar–Oct
Euronext (Lisbon)	8:00–16:30	3:00–11:30	None	Mar–Oct
Euronext (Amsterdam)	8:00–16:40	3:00–11:40	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 repots averages for several trading activity and liquidity measures for E-mini S&P futures for selected intraday subperiods. A trading day (last column) is split into Asia pre EU-open (6 pm to 11:30 EST), EU-open (11:30 pm to 3:30 am), Asia, Europe, the U.S. (9:30 am to 4:15pm). Per minute statistics as well as period totals are reported. The measures include trading volume, number of trades, trade size, the bid-ask spread, market depth.
Market Depth = 0.5*(Best Bid Size + Best Ask Size). The bid-ask spread is almost always one tick. Relative bid-ask spread is the difference between bid and ask prices normalized by the midquote. The statistics for the bid-ask spread and market depth are based on the subsample with available quote data from 2010 to 2018. S&P 500 index averaged 1780 during this subperiod and is 1566 during 2004 to 2018.

	EU-open	Asia pre EU-open	Asia	Europe	the U.S.	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	1.018	1.021	1.021	1.009	1.003	1.011
Bid-Ask Spread, bp	1.56	1.56	1.56	1.54	1.53	1.54
Market Depth, contracts	87.3	77.1	75.8	156.9	452.9	217.6
Market Depth, $M	7.4	6.6	6.5	13.1	37.1	18.0

Table 4
Returns by year
This table reports several key statistics for E-mini S&P futures returns by year. The statistics include return average, standard deviation, and t-statistics. All these statistics are based on annualized log returns (period return times 252). E.g., average return during EU-open is 4.53% annualized in 2004. The entire trading day (last column) is split into EU-open (from 11:30 pm to 3:30 am EST) and the rest of the day (6 pm to 11:30 pm and 3:20 am to 4:15 pm). T-statistic 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 month

We repot main statistics for E-mini S&P futures returns by day of week and by calendar month including return average, t-statistics, standard deviation, and Sharpe ratio. They are based on annualized log returns (period return times 252). E.g., average return during EU-open is 4.80% annualized on Mondays. We split a day into EU-open (from 11:30 pm to 3:30 am EST) and the rest of the day (6 pm to 11:30 pm and 3:30 am to 4:15 pm). T-statistic is computed to account for heteroskedasticity and autocorrelation.

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
Trading Strategy
This table shows profitability of a trading strategy that buys E-mini futures at the start of EU-open and sells them at the end with and without transaction costs ("TC"). We report annualized expected return, standard deviation, Sharpe ratio, and t-statistic. The baseline strategy trades every day, the conditional strategy trades on 30% of days with higher expected EU-return as predicted by volatility and volume from the pre-EU-open Asian session and by the previous day U.S. session return. The strategies pay the entire bid-ask spread by entering at the ask and exiting at the bid.

Trading strategy	Exp. return	Std. dev.	Sharpe ratio	T-stat
Baseline, no TC, %	7.56	4.59	1.65	6.27
Baseline, with TC, %	3.16	4.59	0.69	2.62
Conditional, no TC, %	7.44	3.84	1.94	7.38
Conditional, with TC, %	5.30	3.82	1.39	5.29

Table 7
Conditional EU-open returns
This table shows how market return during EU-open depends on (lagged) market conditions. The predictors, measured at the previous close, include VIX index (implied volatility for one-month SPX options), TED spread (difference between on-month LIBOR and Treasury rates), Term spread (difference between long-term and short-term rates), Sentix Investor Confidence Index of European investors (relative six-month economic outlook for the euro zone), Baker and Wurgler (2007) sentiment, bull-bear spread from AAII Investor Sentiment Survey (mood of U.S. individual investors), University of Michigan Consumer Sentiment Index (U.S. consumer confidence), and weekend indicator. For the columns marked [3] through [7], we focus on short-term predictors based on the per-EU-open Asian session, which include return, volume, and volatility during this period and VIX from previous close relative to its five-day average. T-statistics account for heteroscedasticity and autocorrelation.

	[1]	[2]
Intercept	0.076	0.08
t-stat	7.00	6.99
VIX	0.066	0.15
t-stat	2.37	3.32
TED spread		-0.07
t-stat		-2.03
Term spread		0.00
t-stat		-0.05
EU sentiment		0.05
t-stat		1.45
BW sentiment		-0.02
t-stat		-0.68
AAII retail sentiment		-0.01
t-stat		-0.83
UofM consumer confid.		0.05
t-stat		1.94
Weekend		-0.08
t-stat		-2.60
# Obs.	3649	3649
R^2, %	0.79	1.49

	[3]	[4]	[5]	[6]	[7]
Intercept	0.08	0.08	0.08	0.08	0.76
t-stat	7.18	6.88	7.18	7.06	7.2
Ret Asia	-0.06				-0.01
t-stat	-1.04				-0.28
Volat. Asia		0.11			0.06
t-stat		3.04			1.49
Volume Asia			0.13		0.1
t-stat			3.46		2.47
VIX Shock				0.13	
t-stat				4.08	
# Obs.	3649	3649	3649	3640	3649
R^2, %	0.39	2.44	3.25	3.32	3.61

Table 8
VIX futures returns during EU-open and other intervals
This table reports essential 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, that are not annualized (e.g., minimum return during EU-open is -13.62%). The entire trading day (last column) is split into Asia before EU-open, EU-open, rest of the day until U.S. close ("post-EU-open") and the period around U.S. 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 6pm-11:30pm	EU-open 11:30pm-3:30am	Post-EU-open 3:30am-2pm	U.S.-close 2pm-4:15pm	Total 6pm-4:15pm
Average return, % p.a.	37.47	-46.26	-21.39	-50.83	-81.01
T-statistic	2.69	-5.20	-0.88	-2.20	-2.17
Standard deviation, %	28.26	18.04	49.53	46.90	75.57
Sharpe ratio, p.a.	1.33	-2.56	-0.43	-1.08	-1.07
Skewness	9.00	-2.07	0.61	7.67	2.54
Kurtosis	168.49	24.69	4.65	150.93	30.46
Min, %	-9.49	-13.62	-10.88	-10.89	-19.22
5%	-1.72	-2.02	-4.65	-3.93	-6.79
25%	-0.39	-0.62	-1.92	-1.39	-2.74
50%	0.00	0.00	-0.38	-0.27	-0.68
75%	0.58	0.36	1.42	0.70	1.69
95%	1.86	1.38	5.67	3.92	7.32
Max, %	35.45	5.14	13.03	58.24	59.86
Max drawdown, %	13.52	87.42	90.71	94.54	99.09

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: 6pm to 11:30pm (Asia), 11:30 pm until 3:30 am (EU-Open), 3:30 am to 3 pm (EU and the US), 3 pm to 4:15 pm (US-close). Cumulative return is reset to zero at the start of each interval. Confidence intervals are computed using bootstrap. Intervals expand over time as volatility accumulates.

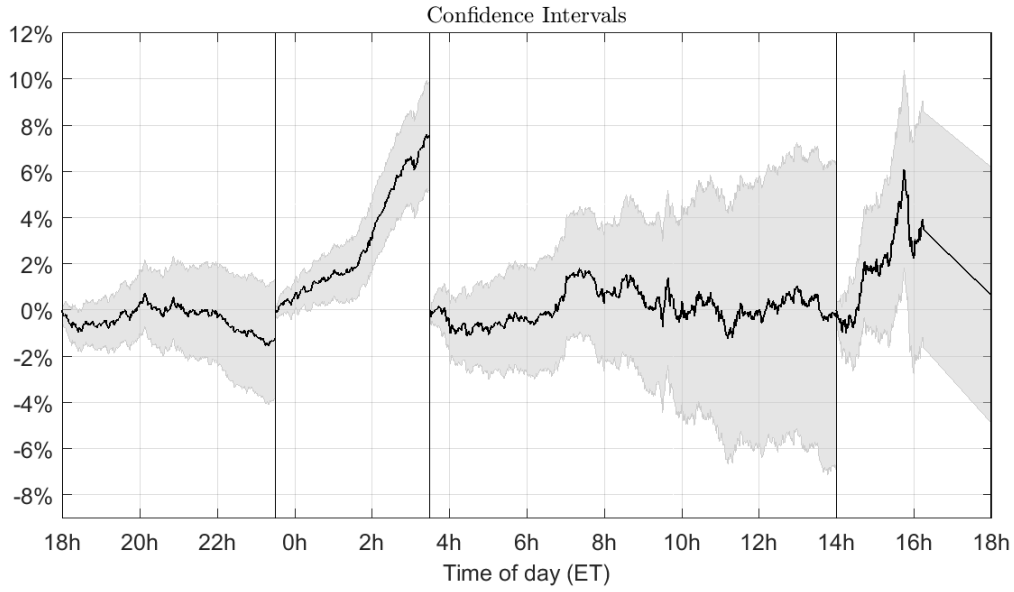


Figure 4
What other intervals have significant returns?
Left (right) panel shows a centered moving average for one-hour (four-hour) cumulative market return during a day. Horizontal dashed lines mark 5% and 1% statistical significance levels. T-statistic is computed to account for heteroscedasticity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

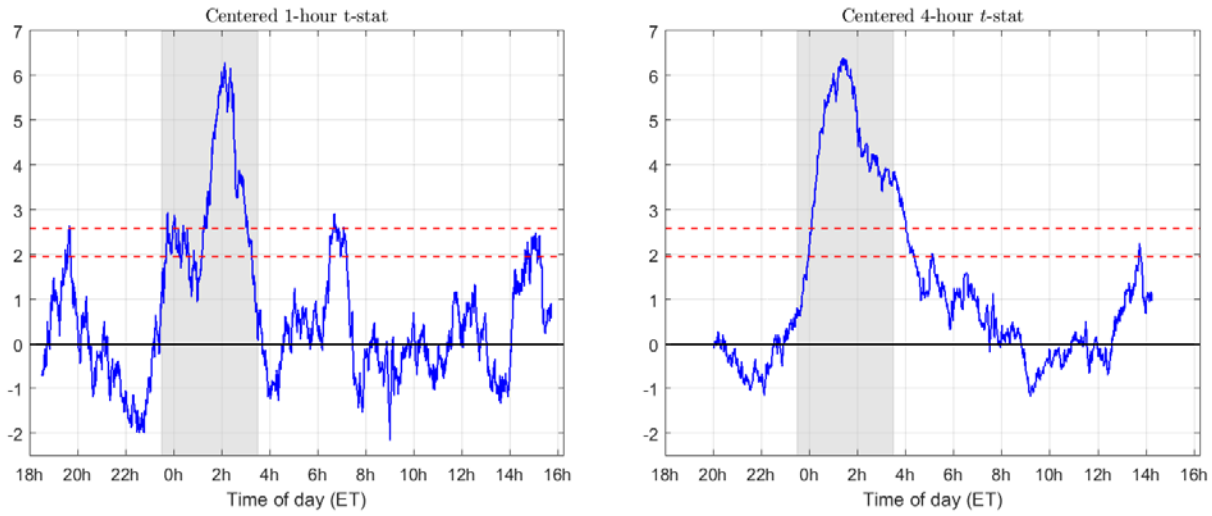
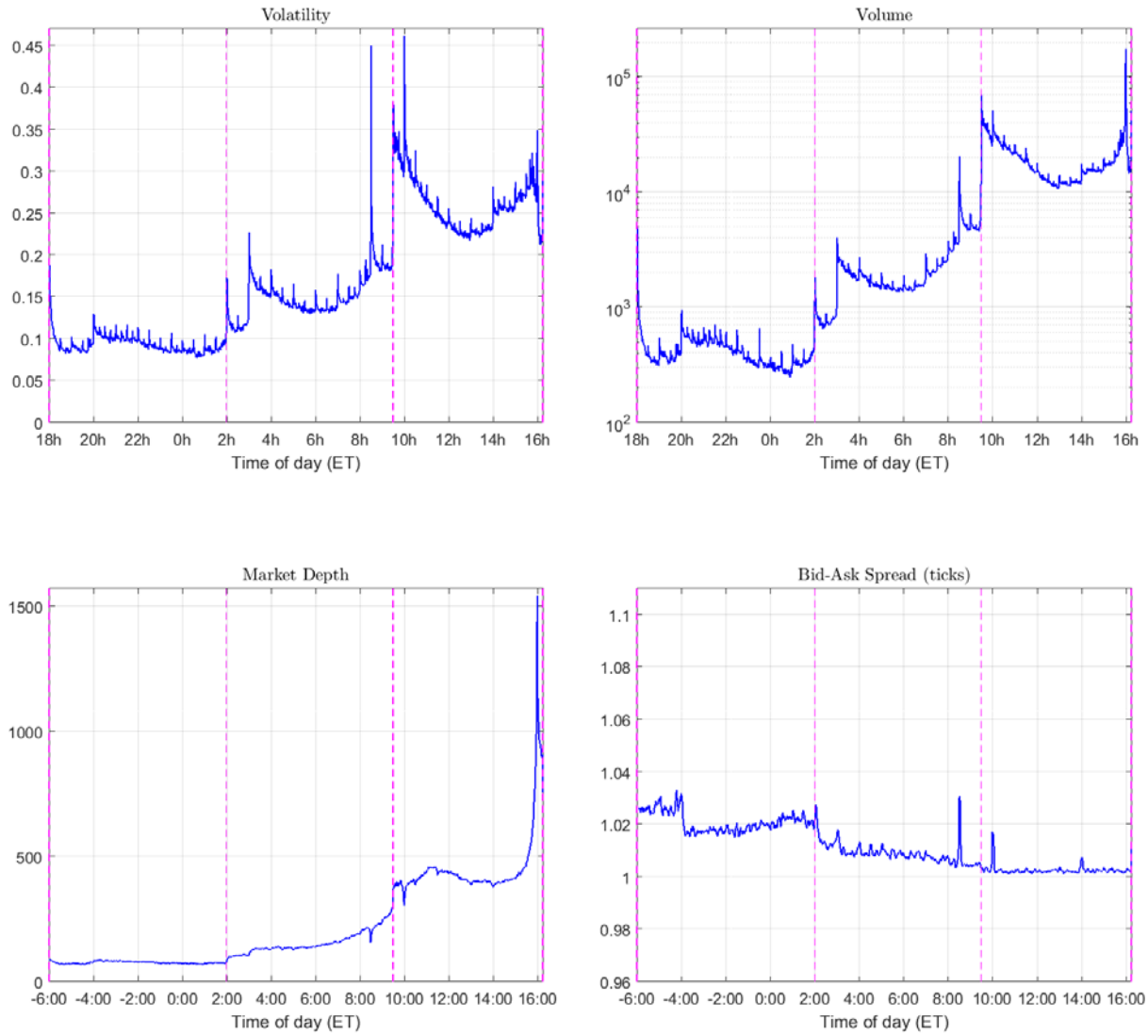


Figure 5
Trading activity and liquidity around the clock
This figure shows how trading activity and liquidity change over a day. Volatility (Panel A) is computed as an annualized standard deviation across one minute realized returns across all days. Trading volume (Panel B) is in future contracts per 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. Figures are plotted at one-minute frequency. Trade size (Panel E) is computed as trading volume in contracts divided by the number of trades. Vertical dashed lines correspond to the European and U.S. market open times.



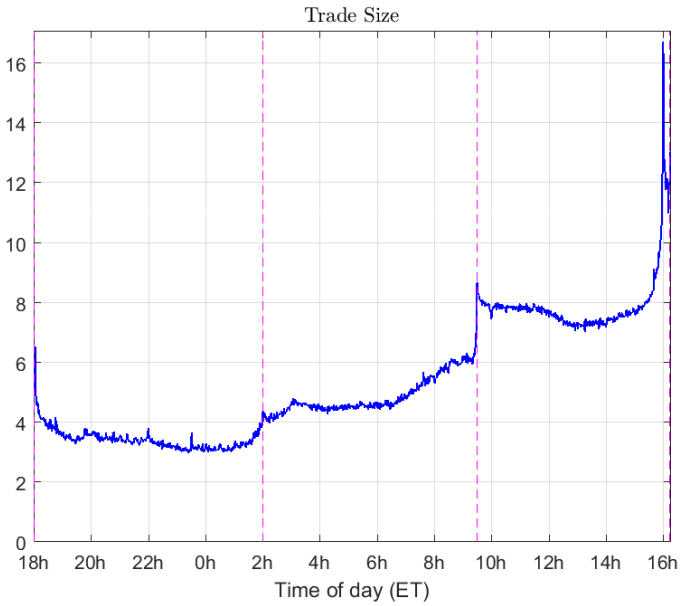

Trade Size
16
14
12
10
8
6
4
2
0
18h
20h
22h
0h
2h
4h
6h
8h
10h
12h
14h
16h
Time of day (ET)

Figure 6

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 (stable line) period and the rest of the day (RoD, volatile line) over the sample period from 2004 to 2018. Vertical dashed lines mark the 2008 financial crisis. Bottom panel repeats the analysis for t-statistics of the cumulative market return. Horizontal dashed lines mark 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 7
Cumulative market return over time
Top panel shows cumulative market return for EU-open (stable line) period and the rest of the day (RoD, volatile line) from 2004 to 2018. Vertical dashed lines mark the 2008 financial crisis. 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 plots a two-year moving average. Market return is computed from E-mini S&P future prices.

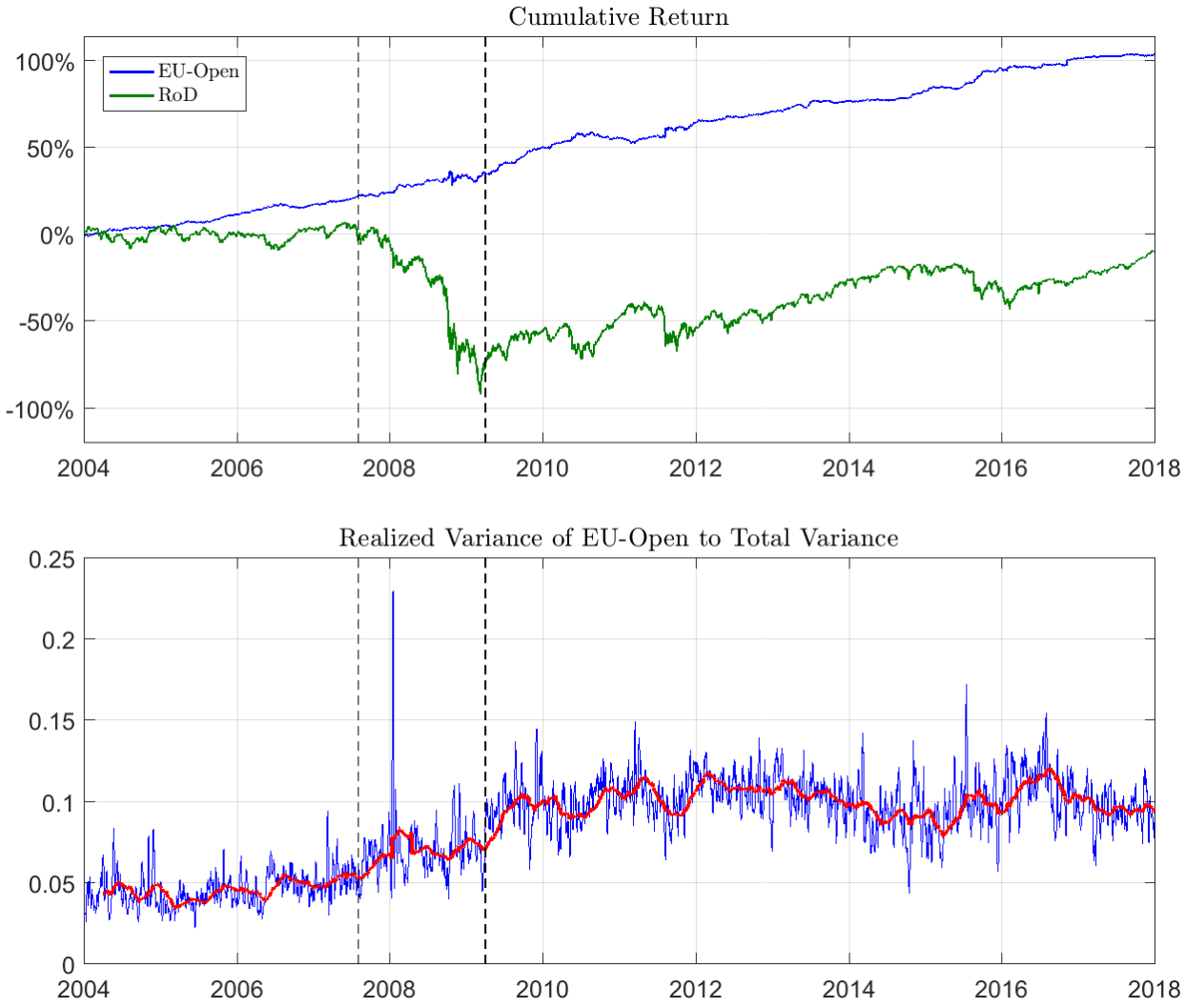


Figure 8

US/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 panels report results in European/US time, while bottom panels report the same results but in Asian time. Asia does not have daylight savings time (DST) while the US and Europe do. During DST ("Summer 1") the US and Europe are one hour ahead of Asia compared to the normal time difference during the rest of the year ("Winter"). The return and volume patterns remain in the US/European time and do not shift (due to DST) with Asian time. Trading volume is futures contracts per minute. Cumulative return is annualized. Vertical dashed lines mark the EU-open period boundaries.

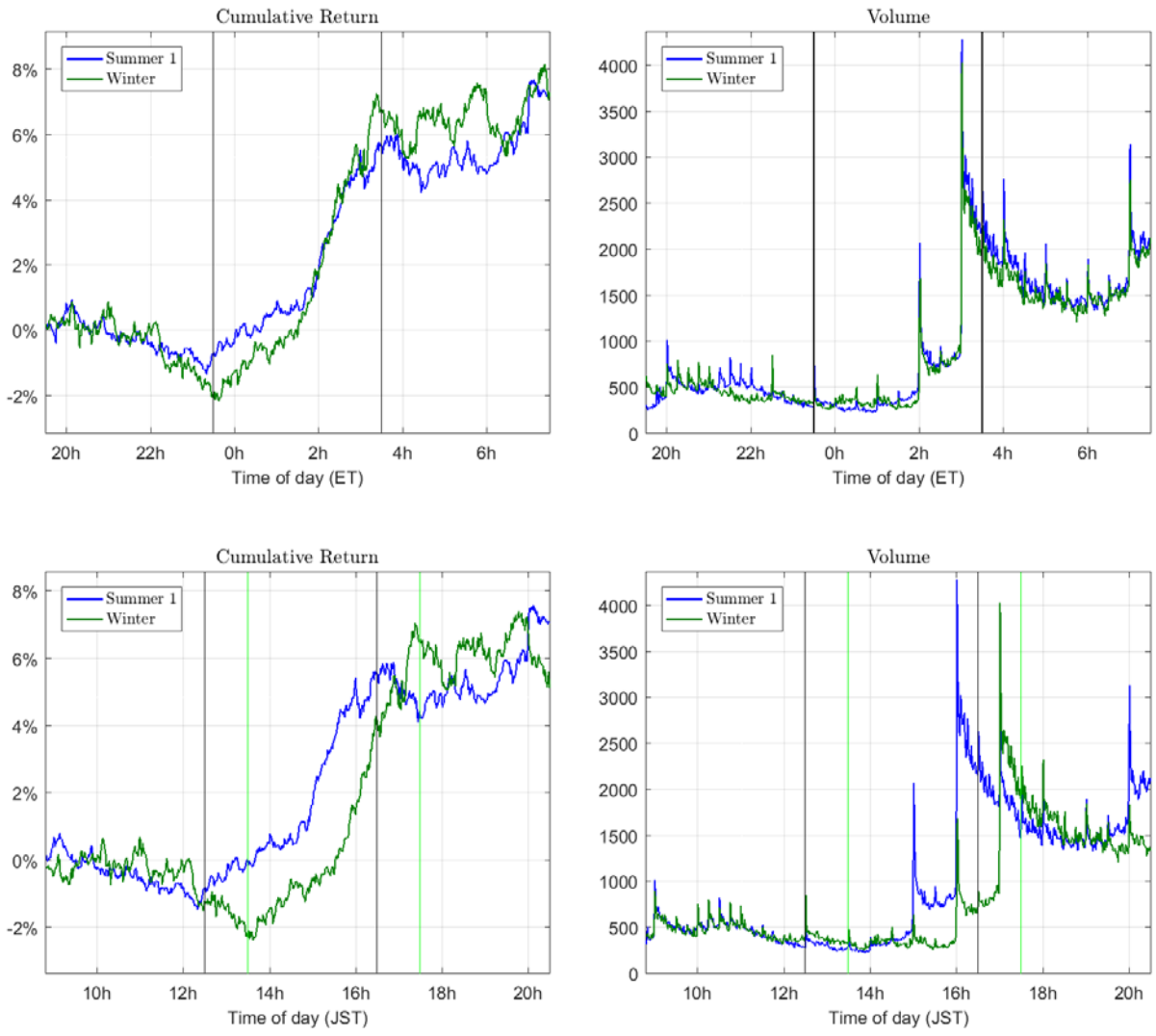


Figure 9
Weekends versus weekdays
This figure compares cumulative market return (left panel) and minute-by-minute trading volume (right panel) during a day for weekends (Mon, Friday-to-Monday) with regular weekdays (non-Mon). There is little difference between the two. Cumulative return is annualized.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

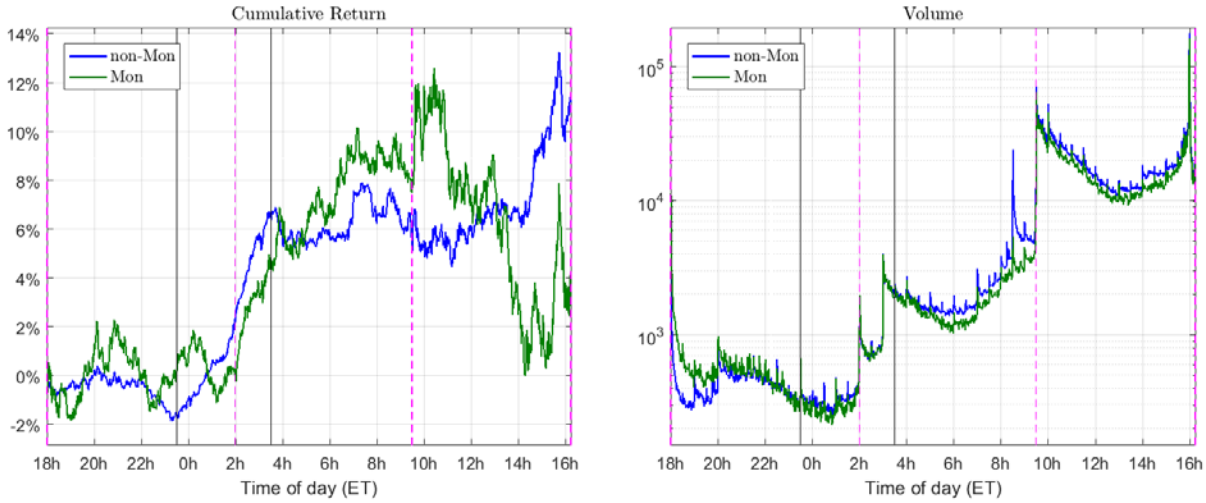


Figure 10
First and second part of the sample
This figure compares cumulative market return (left panel) and minute-by-minute trading volume (right panel) during a day for the first (pre-2011) and second (post-2011) part of the sample period. Trading volume increased markedly during post-2011 but the 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 U.S. market open times.

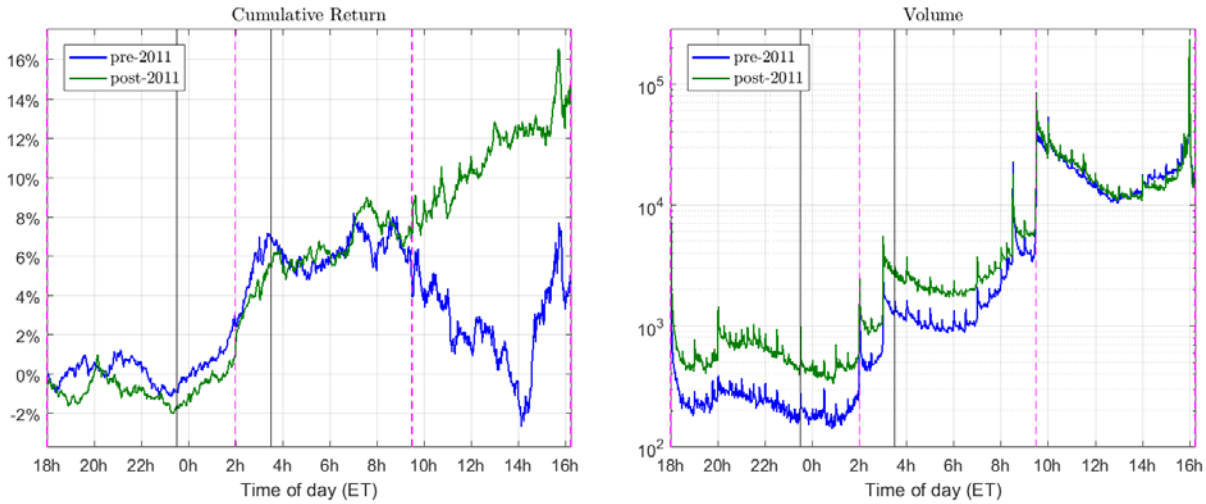


Figure 11
Variance ratio for daily returns
This figure shows how return variance depends on time of the day when prices are taken to compute 24h returns and then their variance. Variance at time *t* is computed as average over all days of squared returns from *t* to *t+24h*. We then report a ratio of variance at time *t* to overall daily average variance (over all starting times). E.g., 1.08 at 0:00h means that variance is 8% higher than average for the 0:00-to-0:00 returns. Variance ratio is often used as measure of how noisy prices are.

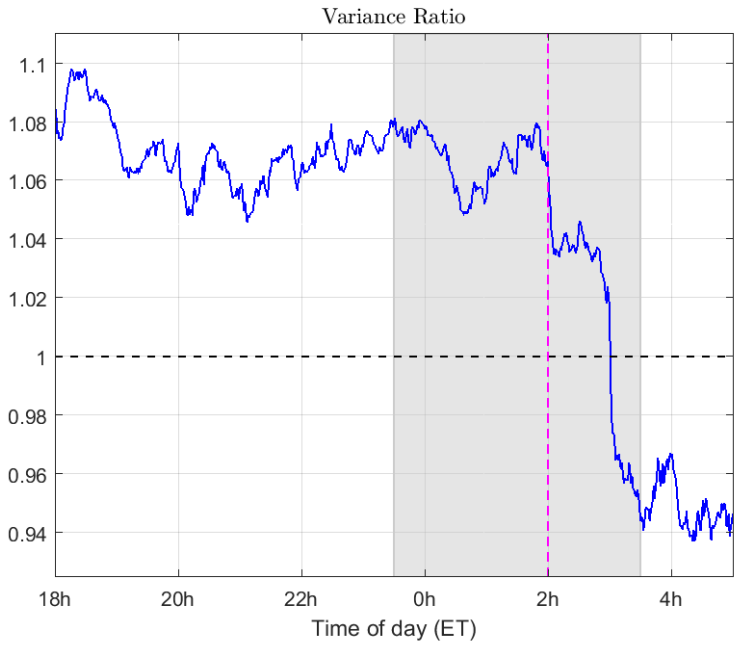


Figure 12

VIX futures returns with confidence intervals

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: 6pm to 11:30pm (Asia), 11:30 pm until 3:30 am (EU-Open), 3:30 am to 3 pm (EU and the US), 3 pm to 4:15 pm (US-close). Cumulative return is reset to zero at the start of each interval. Confidence intervals are computed using bootstrap. Intervals expand over time as volatility accumulates. Extended hours for VIX futures start spanning EU-open on July 2014, and the sample ends in 2018. Bottom panel shows a centered moving average for one-hour (four-hour) cumulative VIX future return during a day. Horizontal dashed lines mark 5% and 1% statistical significance levels. T-statistic is computed to account for heteroscedasticity and autocorrelation. EU-open period is shaded grey. One-minute time step.

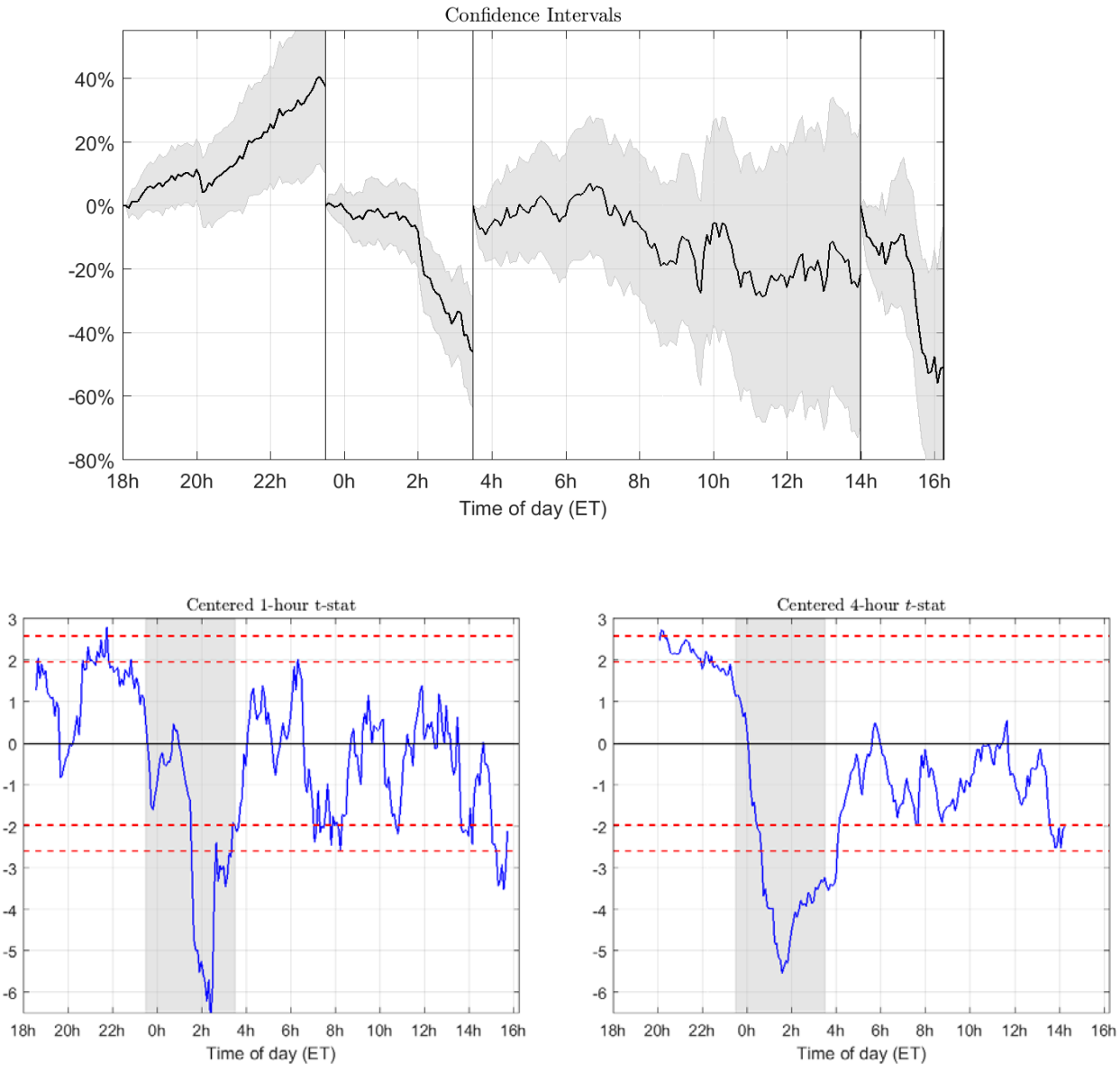
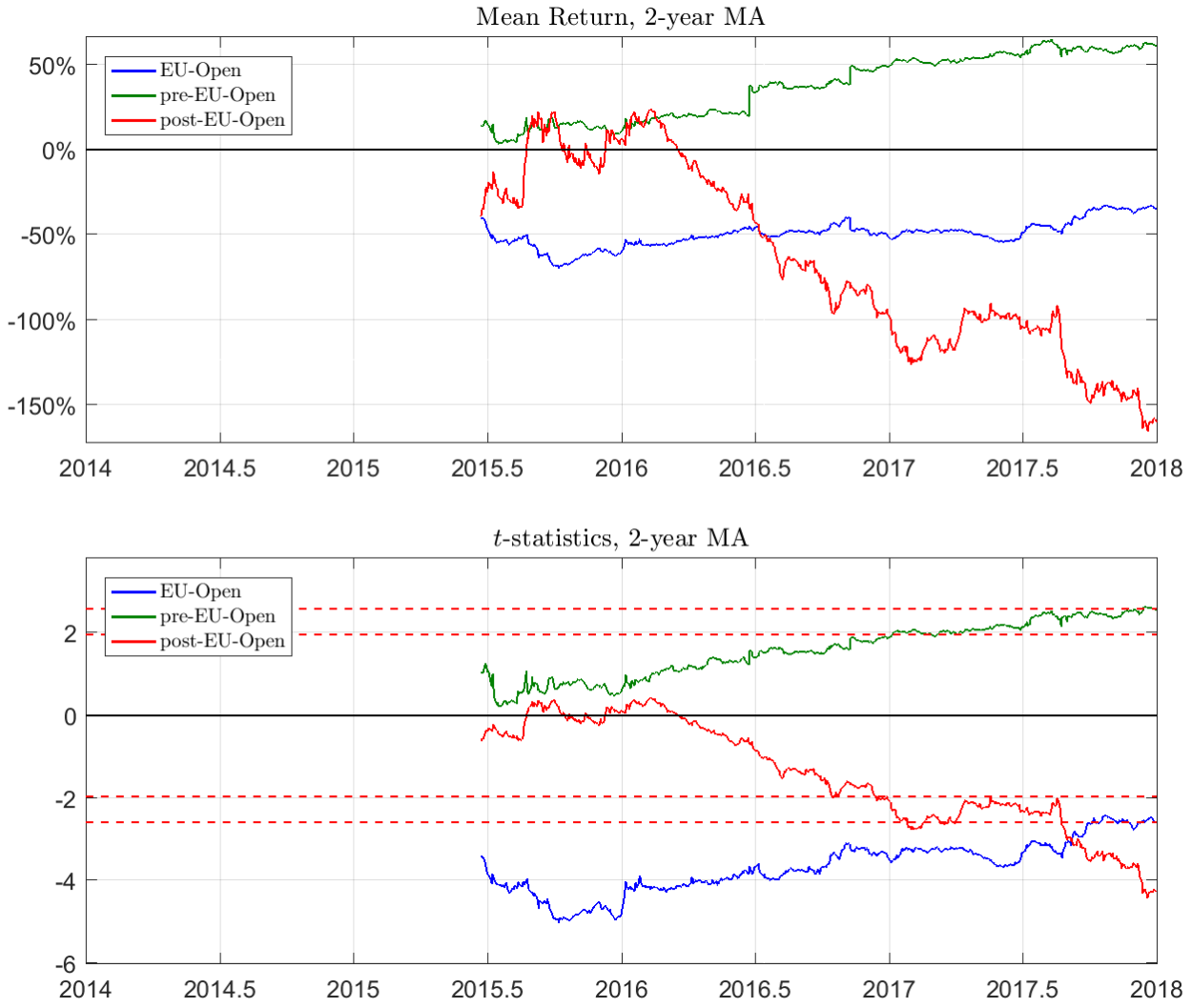


Figure 13

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 2018. Bottom panel repeats the analysis for t-statistics of the cumulative VIX future return. Horizontal dashed lines mark 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.



Appendix

This appendix presents additional figures and tables.

Table A.1
Excess market returns for intraday intervals

This table reports essential statistics for E-mini S&P future returns including return average, t-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. All these measures are computed from annualized log returns. We also report return distribution percentiles, that are not annualized. We report intraday intervals including overnight session before EU-open, first and second halves of EU-open, Asian, European, and the U.S. sessions, the period between U.S. 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 6pm-11:30pm	EU-open Part 1 11:30pm-1:30am	EU-open Part 2 1:30am-3:30am	Asia 6pm-2am	Europe 2am-9:30am	U.S. 9:30am-4:15pm	Post U.S.-close 4:15pm-6pm	Total 6pm-6pm
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 A.2
Trading activity over time
The table shows trading activity during Asian, European, and U.S. sessions by year. Note how Asia 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				Percentage of total		
	Asia	Europe	U.S.	Total	Asia	Europe	U.S.
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 A.3

Market return for extended sample by year.

This table reports several statistics for E-mini S&P futures returns by year. The main sample is from 2004 to 2018, in this table, we extend the sample to 1998. However, Asian session only became liquid in 2004 (Table A.2), and E-mini S&P prices are only available in Tick data starting at 2 am (middle of EU-open) until May 2003, when the trading hours were extended to 6 pm or nearly 24 hours. The statistics include return average, t-statistics, standard deviation, and Sharpe ratio. All these statistics are based on annualized log returns (period return times 252). The entire trading day (last column) is split into EU-open (from 11:30 pm to 3:30 am EST) and the rest of the day (6 pm to 11:30 pm and 3:20 am to 4:15 pm). T-statistic is computed to account for heteroskedasticity and autocorrelation. Last row reports sample average.

	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

Figure A.1
Returns in calendar and variance time
This figure shows cumulative market return over a trading day in regular calendar (left) and variance (right) clocks. By construction, each minute has the same return variance in variance clock. Each minute in regular is resized proportional to its average variance contribution. Thus, the cumulative return trajectory does not change but the horizontal axis is transformed. Market return is computed from E-mini S&P future prices. Cumulative return is annualized by multiplying period return by 252.

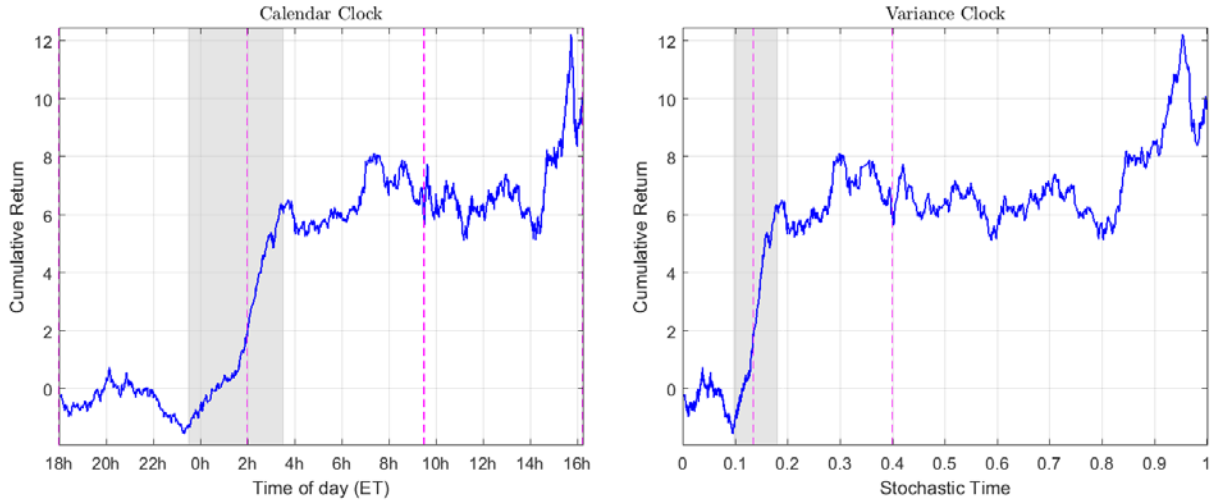


Figure A.2
Cumulative returns for baseline and conditional strategies over time
The strategy buys E-mini future at the start of EU-open and closes position at EU-open end. Top and bottom panels show cumulative returns before and after transaction costs, respectively. Conditional strategy trade only on half of days with high expected EU-open return. Each trade involves the same capital. Trading costs are equal to the bid-ask spread. Vertical dashed lines mark the 2008 financial crisis.

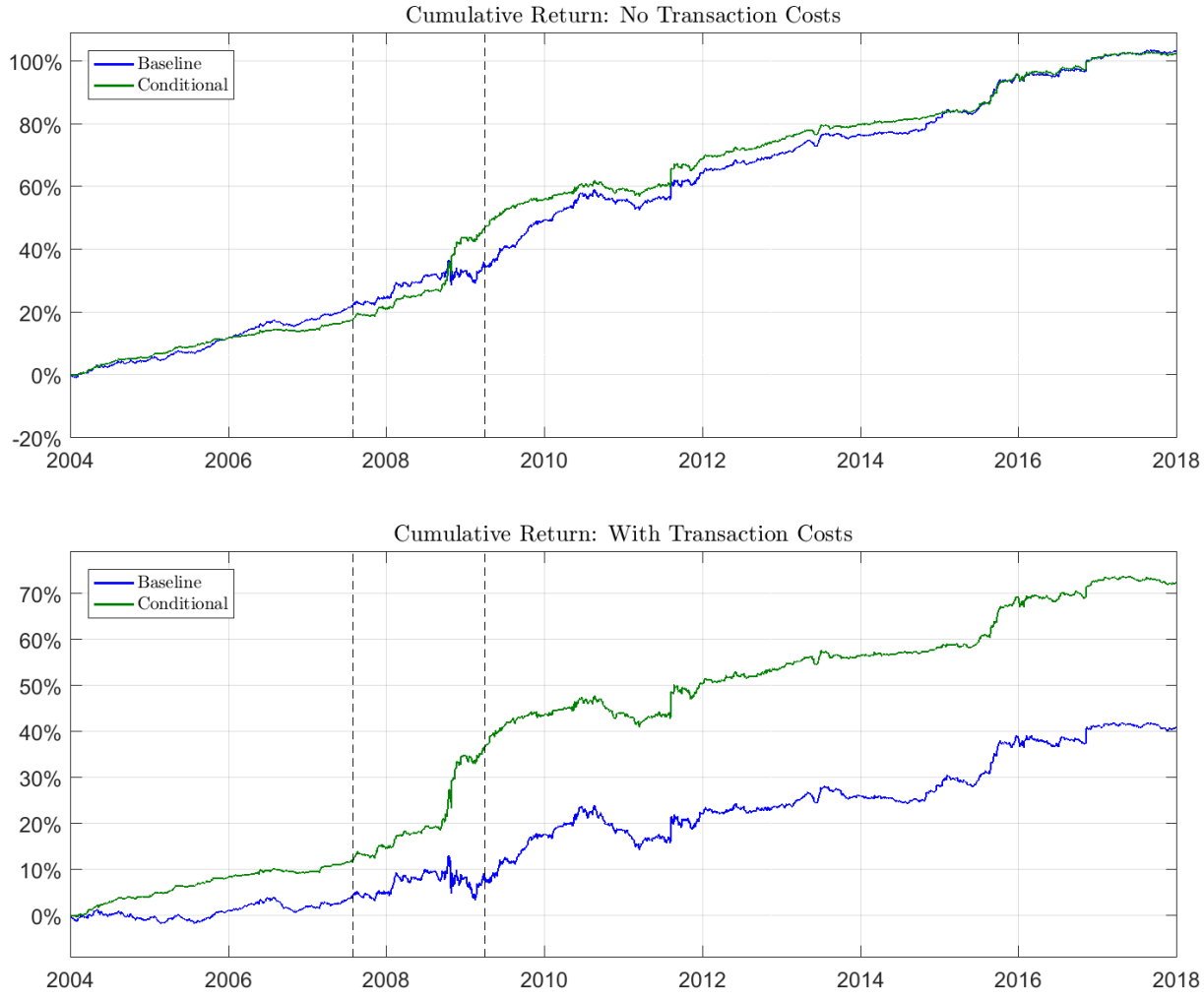


Figure A.3
Cumulative returns for VIX futures over the sample period

