

Internet Appendix to

Market Return Around the Clock: A Puzzle

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This appendix describes how volatility, volume, and liquidity change over a day (Section IA.1), explores alternative definitions for EU-open period (Section IA.2), tests the inventory risk hypothesis (Section IA.3), and presents additional figures and tables.

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

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

Second, volatility and volume are U-shaped during the US session and pre-US European session. For the pre-US European session, volume is much higher approaching the US open as US investors arrive at the market. For the US session, volume is the highest at 4:00 pm then drops during the last 15 minutes. The Asian session's pattern differs. Volatility and volume spike at Hong

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

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

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

IA.2 Alternative definitions of EU-open

In this section, we explore how the uncertainty resolution hypothesis links investor arrival, uncertainty, and returns while also exploring alternative definitions of the EU-open period. European investors are more likely to arrive during (i) the second part of EU-open and (ii) especially around the opening time for the Frankfurt and London exchanges. Uncertainty resolution accelerates during these times, and returns accumulate faster as the uncertainty discount shrinks. The consistent results for the two alternative periods help alleviate the concern about how we define EU-open.

We confirm this prediction for (i) and (ii). First, many European investors arrive around 2:00 am ET (8:00 am EU time) when the Frankfurt exchange opens. Indeed, E-mini trading volume spikes around this time. Table IA.8 shows that the results for the main uncertainty tests are stronger for one hour from 1:30 am to 2:30 am. This hour accounts for 5.0% of the 7.6% total EU-open S&P return and for -23% of the -46% total EU-open VIX futures return. This hour also accounts for about half of the magnitude for how uncertainty measures, including VIX change, pre-EU-open volume and volatility, and Twitter uncertainty index, predict future returns during EU-open.

Second, while some investors rush to trade as soon as they wake up (during the first part of EU-open that ends at 7:30 am EU time), most European investors arrive in the second part of EU-open, after 7:30 am EU time, around the time when major EU equity markets open. Indeed, Table IA.5 confirms that volume, volatility, and trade size are 3.5 times, 36%, and 33% larger in the second part of EU-open than in the first part. Table IA.8 shows that the second part accounts for most of EU-open's uncertainty resolution and market return – a -41.7% VIX return and a 5.9% S&P return. Market return during the second part strongly depends on uncertainty measures, while this relation is positive but not significant for the first part.

IA.3 Inventory risk

What if some investors are averse to the overnight period because of lower liquidity or fear that the market moves while they are away? To avoid this period, investors can hedge or not carry positions overnight. They will pay a premium to liquidity providers for taking this risk. Inventory risk arises because liquidity providers are risk-averse and have limited capital. They are required to take customer order flow and thus hold suboptimal portfolios. The premium for inventory risk increases in undesired position size, asset volatility, dealer's risk aversion, and expected holding period. This idea goes back to at least Stoll (1978). E.g., Bessembinder (1992) shows that returns for some futures vary with the net holdings of hedgers after controlling for systematic risk. Overnight returns should be positive even without trading because equities are in positive net supply – whoever carries positions overnight is compensated for the overnight risk. According to this channel, average returns should be positive every hour during the night, including EU-open, which is rejected by the data.

The effect of inventory risk on average return should not be confused with its effect on price reversal. If investors buy at the close, their price pressure causes positive returns that subsequently reverse overnight. The price increase at the close must be offset by the price reversal

overnight on average for a zero net return. If the two price impacts do not match, prices can be manipulated. Alternatively, if investors sell at the close, closing return will be negative, followed by a positive overnight reversal, including EU-open. Inventory risk implies a price reversal after an inventory shock at the close. But, its net effect on the average return is zero. Dealers can properly estimate expected imbalances (e.g., if investors repeatedly buy at EU-open) from 15 years of daily data. Only unexpected imbalances, which are 50/50 buy/sell under rational expectations, have price impact, and thus the net effect of these imbalances on the average return is zero.

Inventory risk seems intuitive and plausible, but this hypothesis struggles to explain *average* EU-open returns. Its predictions do not line up with the data. Inventory risk models cannot explain why dealers are compensated only during EU-open. Overnight return must be highly positive in every single night hour; instead, dealers lose money because of a slightly negative return in the pre-EU-open period, -1.25% p.a. in Table IA.1 and Figure 1. An opportunistic investor, who carries no inventory risk, can earn the same EU-open return as the dealers by “cutting the line” and buying right before EU-open. Section V.C shows that this strategy is profitable after costs. The free-rider can boost returns by buying at the bid as she loses nothing if the limit order is not executed. Thus, inventory risk cannot explain negative pre-EU-open returns combined with large positive EU-open returns, but uncertainty resolution can.

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

We directly test whether the inability to trade at night or its perceived illiquidity affects overnight returns. First, while investors can trade on a regular night, the E-mini market is closed on the weekend from 4:15 pm on Friday to 6:00 pm on Sunday. Thus, the inventory risk premium should be larger over weekends than on weekday nights. Figure IA.12 compares cumulative return and volume on weekdays and weekends. Weekend returns are noisier as they are four times less frequent. If anything, EU-open returns are lower on weekends than on the other days, 4.8% versus 8.2%. Non-trading periods do not carry a higher premium in our sample.

We further test whether night illiquidity leads to a higher premium for inventory risk by comparing the earlier and later parts of the sample, pre- and post- 2011. The overnight liquidity increased substantially during the sample period. Figure IA.13 shows that while volume remained unchanged during the US hours, it doubled for Europe and quadrupled for Asia. Overnight liquidity improved, but the trajectories for cumulative returns during the first and second parts are remarkably similar through the entire night, including EU-open. Returns diverge only during the US hours, due to the effect of the financial crisis in the pre-2011 period. Overnight liquidity does not affect EU-open return, contrary to the inventory risk hypothesis.

We also study inventory shocks directly. If dealers receive no inventory shock at US close, as reflected by zero order imbalance, then high EU-open returns should disappear without price pressure at the close. But EU-open returns remain large for the subsample with a zero order imbalance. Following Easley, Lopez de Prado, and O'Hara (2016), we estimate order imbalance with a block volume classification approach using 10-second bars and tick rule. We rank days by their order imbalance during the last hour of the US session and compute next-day EU-open return for two samples with low order imbalance: with order imbalance between 25% and 75% percentiles and with imbalance between 40% and 60%. Panel A of Table IA.9 confirms that imbalance is only 0.4% for two samples. EU-open returns are large – 6.70% and 8.44% for the 25-75 and 40-60 samples – statically significant, and close to the full sample average (7.6%). Pre-EU-open returns are slightly negative. Figure IA.8 shows that the cumulative returns over the day for the 40-60 sample are similar to the full-sample returns in Figure 1. Although order imbalance might explain return reversal, it does not affect the average EU-open returns.

Finally, in a direct horse race, inventory risk is subsumed by uncertainty resolution. Inventory risk implies that order imbalance at US close predicts return reversal at EU-open. We compute order imbalance and VIX change – common proxies for inventory risk and uncertainty resolution – during the last hour of the US session. Panel B of Table IA.9 shows that both variables predict the EU-open return in univariate regressions (imbalance has a much lower R^2 , 1.9% versus 7.2%). But in a joint regression, the coefficient for order imbalance becomes almost zero with a t -statistic of -0.3, while VIX change has a t -statistic of 3.1. Overall, uncertainty resolution explains return reversal at EU-open better than inventory risk.

Table IA.1**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 the local time zone and Eastern Time. Daylight Savings Time (DST) in Europe extends from the last Sunday in March to the last Sunday in October; DST in the US extends from the second Sunday in March to the first Sunday in November. Additional exchanges that open at 2:00 ET: Moscow, Johannesburg, Tel-Aviv, Saudi, Bursa Istanbul; at 3:00 ET: Euronext (Amsterdam, Brussels, Lisbon, London), Swiss, Spanish, Milan, Stockholm: and at 9:30 ET: Toronto, Mexico. Note that in Frankfurt there are two venues: Xetra, which is open 9:00-17:30, and Borse Frankfurt, which is open 8:00-20:00.

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

Table IA.2**Excess market returns for intraday intervals**

This table reports essential statistics for E-mini S&P future returns, including average return, *t*-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. These measures are computed from annualized log returns and, when applicable, are reported as a percent. We also report return distribution percentiles, which are not annualized. Intraday intervals include the overnight session before EU-open, first and second halves of EU-open, Asian, European, and US sessions, the period between US close (4:15 pm) and E-mini re-open (6:00 pm), 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 6:00 pm- 11:30 pm	EU-open 1 st Half 11:30 pm- 1:30 am	EU-open 2 nd Half 1:30 am- 3:30 am	Asia 6:00 pm- 2:00 am	Europe 2:00 am- 9:30 am	US 9:30 am- 4:15 pm	Post US- close 4:15 pm- 6:00 pm	Total 6:00 pm- 6:00 pm
Average return, % p.a.	-1.25	1.70	5.90	1.80	4.39	3.44	-2.83	6.80
<i>t</i> -statistic	-0.95	2.51	5.85	1.21	2.16	0.89	-2.89	1.39
Standard deviation, %	5.01	2.57	3.84	5.67	7.73	14.75	3.73	18.63
Sharpe ratio, p.a.	-0.25	0.66	1.54	0.32	0.57	0.23	-0.76	0.36
Skewness	-2.14	-0.23	1.46	-1.37	-0.13	-0.50	-1.68	-0.42
Kurtosis	37.56	36.22	42.00	35.02	11.33	15.27	84.37	16.80
Min, %	-4.06	-2.11	-2.58	-5.41	-3.23	-9.15	-4.61	-12.01
5%	-0.41	-0.18	-0.28	-0.47	-0.71	-1.43	-0.24	-1.73
25%	-0.10	-0.04	-0.07	-0.11	-0.18	-0.35	-0.06	-0.39
50%	0.00	0.00	0.02	0.00	0.02	0.06	0.00	0.08
75%	0.11	0.05	0.11	0.13	0.23	0.43	0.04	0.54
95%	0.37	0.20	0.35	0.45	0.71	1.26	0.22	1.57
Max, %	2.94	1.87	3.81	3.11	3.70	7.53	3.69	11.28
Max drawdown, %	25.35	3.37	8.44	10.35	30.28	44.55	0.00	61.89

Table IA.3**Trading activity over time**

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

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

Table IA.4**Market return for the extended sample by year**

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

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

Table IA.5**EU-open first half versus second half**

We split EU-open into two two-hour periods: from 11:30 pm to 1:30 am ET (1st half) and from 1:30 am to 3:30 am ET (2nd half). The table reports average annualized return, standard deviation, contract trading volume, and trade size for E-mini S&P 500 futures and VIX futures. The statistics are computed over the period from January 2004 to July 2018 for E-mini S&P 500 futures and over the period from June 22, 2014 to July 2018 for VIX futures. We also report the difference between the two periods and *t*-statistic for the difference, which is adjusted for heteroskedasticity and autocorrelation.

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

Table IA.6**How do EU-open returns depend on market variables?**

We show how EU-open return depends on macro variables measured at the previous close: VIX index, short-term Treasury rate, term spread (the difference between long-term and short-term rates), TED spread (the difference between one-month LIBOR and Treasury rates), bull-bear spread from AAI Investor Sentiment Survey (mood of US individual investors), Baker and Wurgler (2006) sentiment, University of Michigan Consumer Sentiment Index (US consumer confidence), and a weekend indicator. *t*-statistic accounts for heteroskedasticity and autocorrelation.

	EU-open return
VIX	0.0168** [2.2]
Treasury bill	0.0079 [0.8]
Term spread	0.0076 [0.4]
TED spread	-0.1518 [-1.6]
Retail invest sent.	-0.0836 [-0.7]
BW sent.	0.1534 [1.2]
UMich. consumer sent.	0.0048* [1.8]
Weekend	-0.0306 [-0.9]
Intercept	-0.5834 [1.6]
R^2	0.017
Num. Obs.	3,654

Table IA.7**Returns by weekday and calendar month**

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

Panel A

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

Panel B

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

Table IA.8**Alternative definitions of EU-open**

The table reports the results for the main uncertainty resolution tests for EU-open (“Full”, four hours) and its alternative definitions. We consider one hour centered on the opening of EU stock market (“Middle,” 1:30 to 2:30 am), the first part (11:30 pm to 1:30 am), and the second part (1:30 to 3:30 am). The first set of rows reports return averages for E-mini S&P and VIX futures and the corresponding t -statistics in brackets. The second set of rows reports univariate regressions of return during a given EU-open subperiod on an uncertainty measure. The predictors include VIX change on a prior day, shocks to log volume, and volatility during night pre-EU-open, Twitter-based economic uncertainty index (TEU) by Baker, Bloom, Davis, and Renault (2020) on prior close. t -statistic is adjusted for autocorrelation and heteroskedasticity.

	EU-open			
	Full 11:30-3:30	Middle 1:30-2:30	1 st Part 11:30-1:30	2 ^d Part 1:30-3:30
Return, E-mini S&P	0.0761*** [6.4]	0.0508*** [6.2]	0.0169** [2.5]	0.0591*** [5.9]
Return, VIX Futures	-0.463*** [-5.2]	-0.230*** [-5.2]	-0.046 [-0.8]	-0.417*** [-5.0]
Univariate Regressions, Dep. Variable: S&P Return				
VIX Change	0.0998*** [4.1]	0.0375*** [2.6]	0.0162 [1.3]	0.0836*** [4.6]
Volume, pre-EU-open	0.1397*** [3.5]	0.0883*** [2.8]	-0.0063 [-0.2]	0.1460*** [4.0]
Volatility, pre-EU-open	0.4569*** [3.3]	0.2564*** [3.0]	0.0178 [0.2]	0.4391*** [4.2]
Twitter Uncertainty	0.0007*** [3.2]	0.0003*** [2.7]	0.0002* [1.8]	0.0005*** [3.2]

Table IA.9
Inventory risk and EU-open return

Panel A. Zero order imbalance sample

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

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

Panel B. Uncertainty or price pressure?

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

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

Figure IA.1

Cumulative returns: quote midpoint versus trade price

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

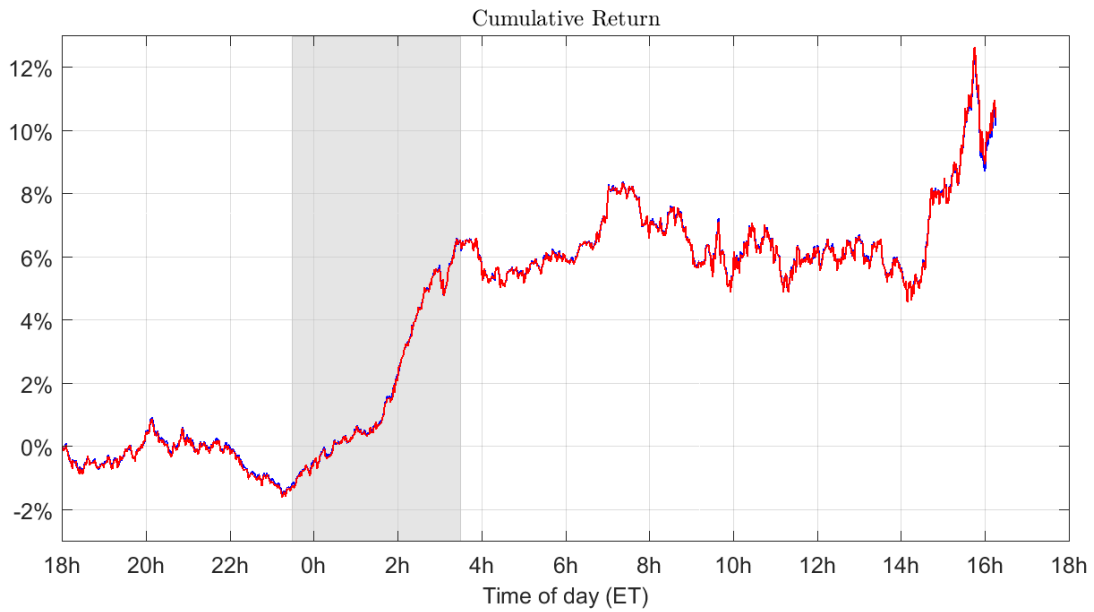
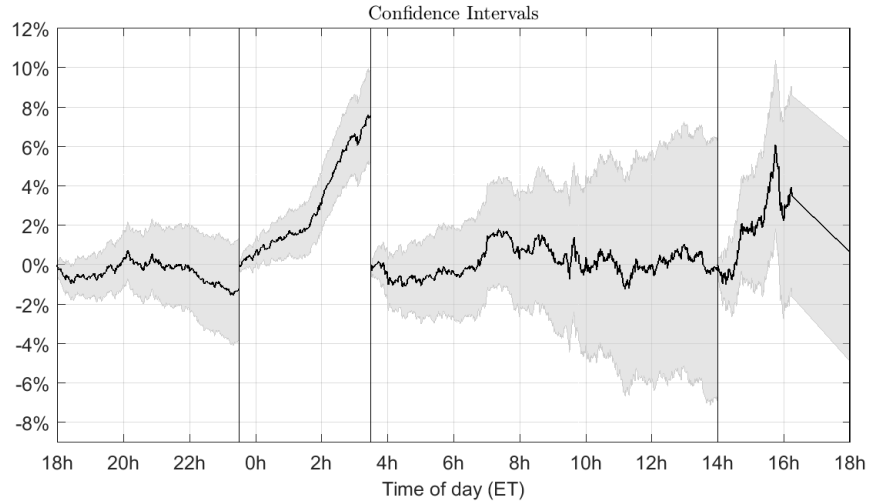


Figure IA.2

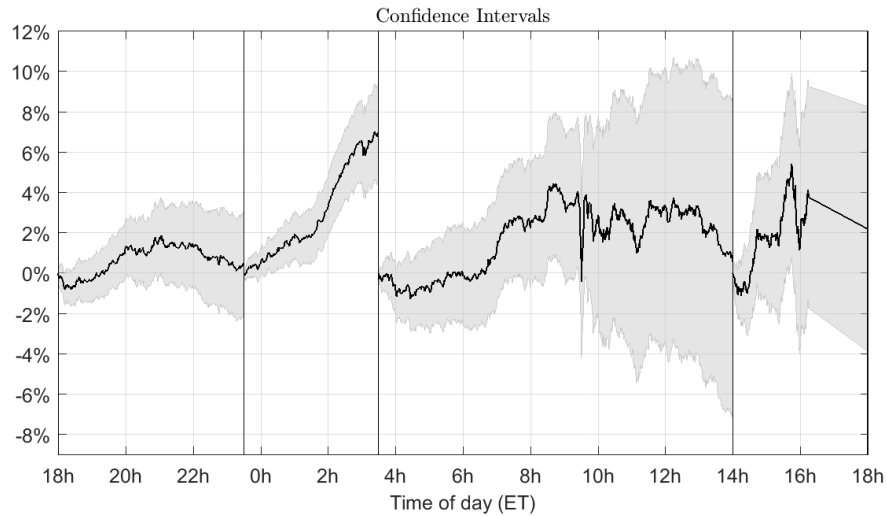
Returns for E-mini S&P 500, Nasdaq 100, and Dow index futures

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

Panel A. E-mini S&P 500



Panel B. E-mini Nasdaq 100



Panel C. E-mini Dow

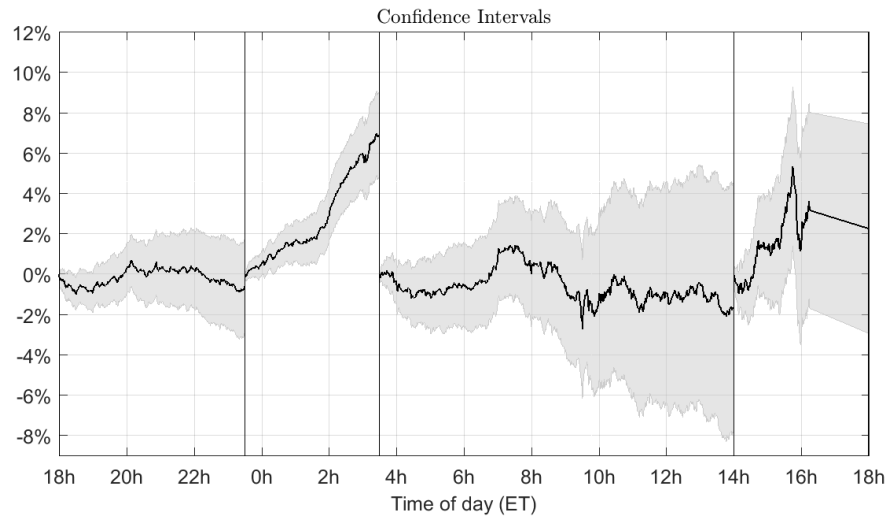


Figure IA.3
Cumulative market returns over time

The top panel shows cumulative market return for EU-open (blue, stable line) period and the rest of the day (RoD, green, volatile line) from 2004 to 2018. Vertical dashed lines indicate the 2008 financial crisis (August 01, 2007 to April 01, 2009). The bottom panel shows the 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. The thick red line shows a two-year moving average. Market return is computed from E-mini S&P future prices.

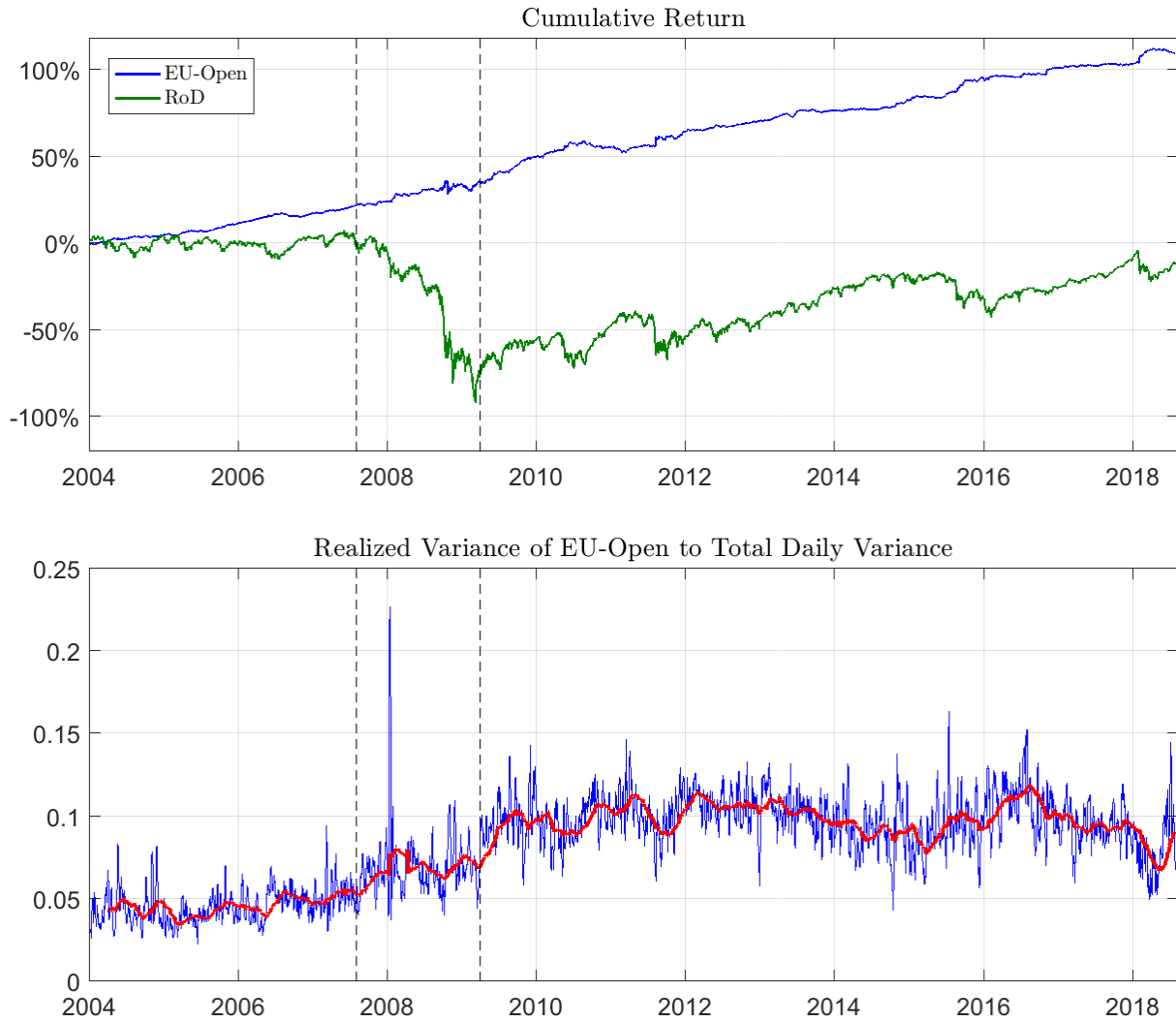


Figure IA.4

Cumulative returns for VIX futures over the sample period

This figure the cumulative VIX futures return during the Asian session before EU-open (green, increasing line), EU-open (blue, decreasing line), and the rest of the day post EU-open (red, volatile line) over the sample period from June 22, 2014 to July 2018.

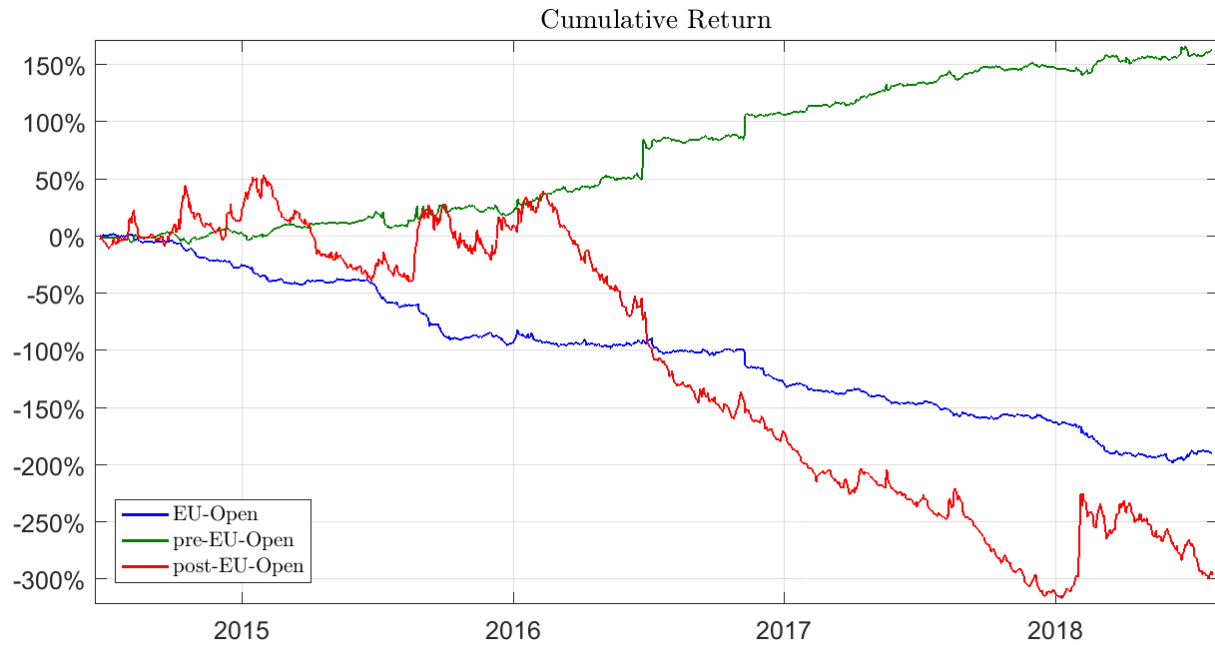


Figure IA.5

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

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

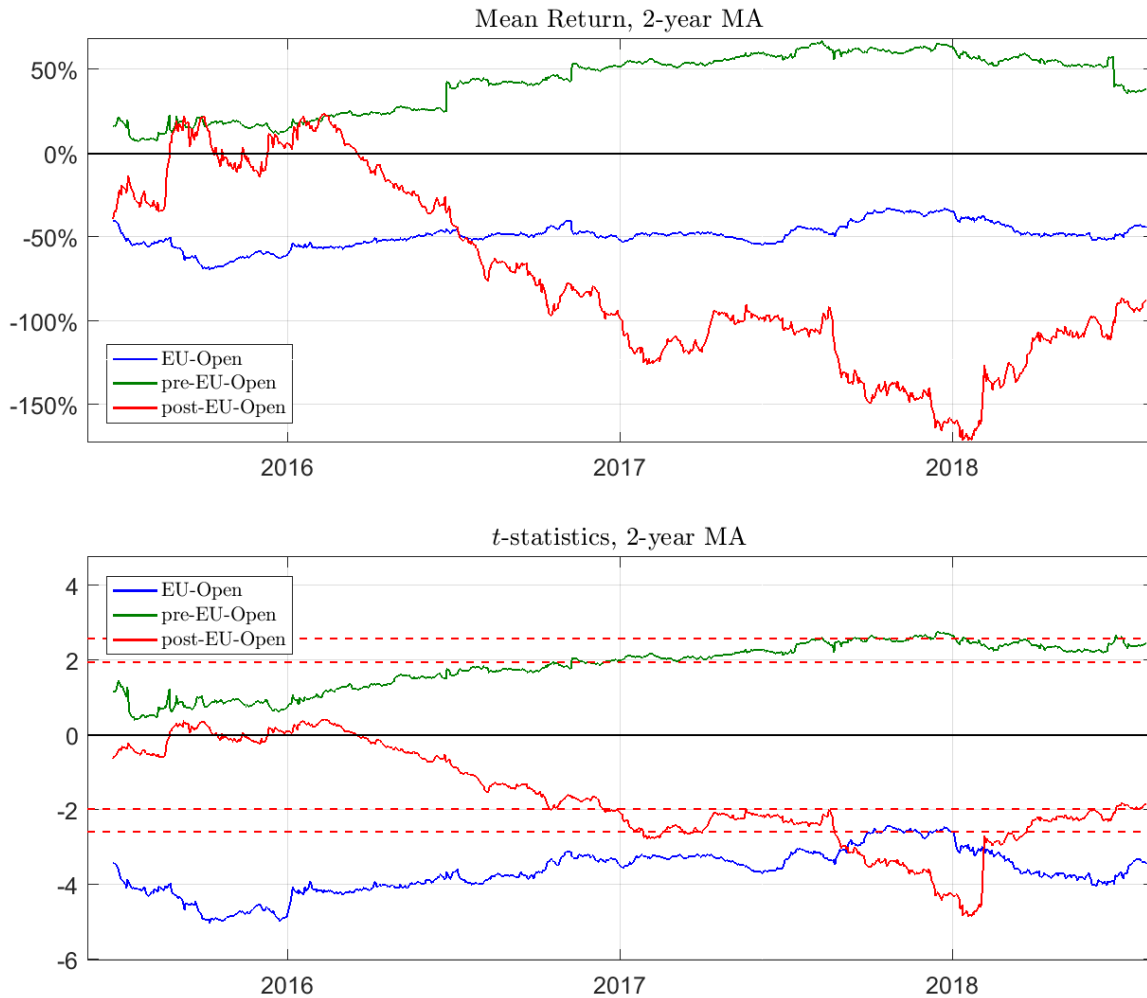


Figure IA.6

Cumulative returns for sample with zero order imbalance

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

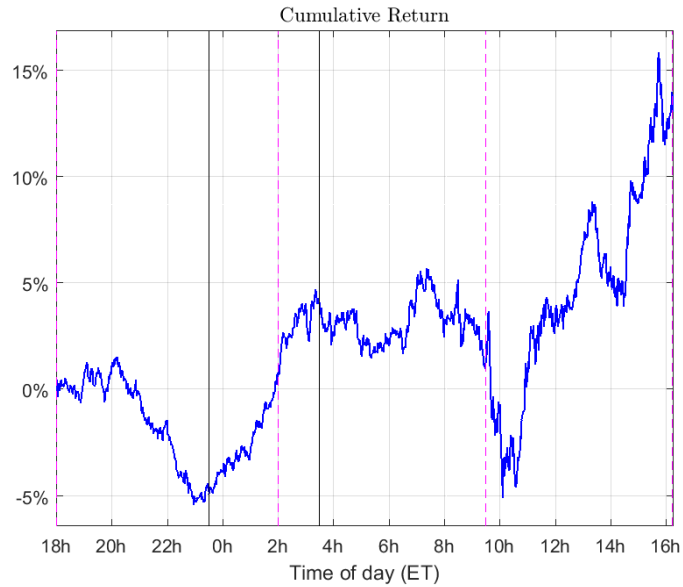


Figure IA.7

Cumulative returns for baseline and conditional strategies over time

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

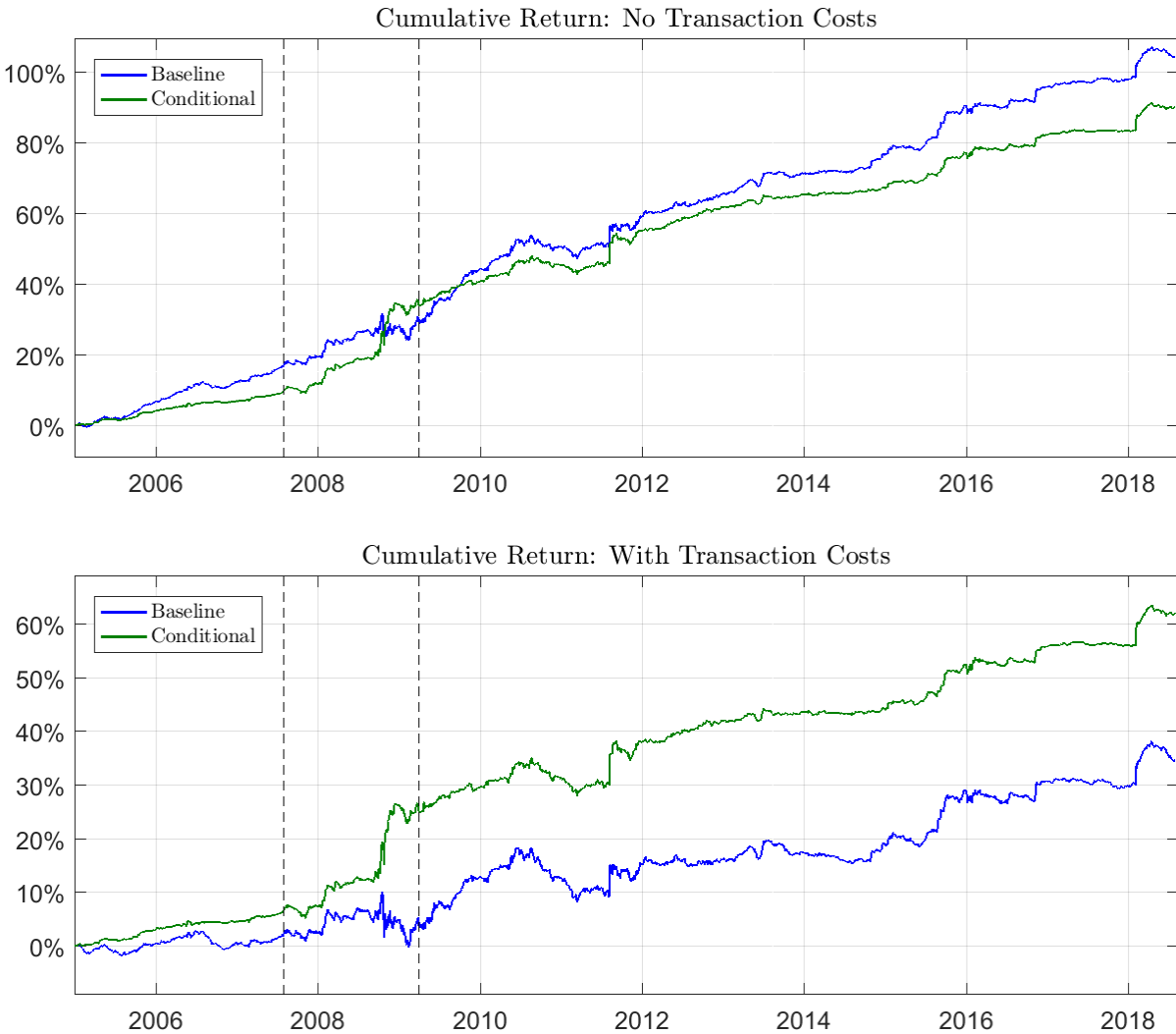


Figure IA.8

Conditional trading strategy

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

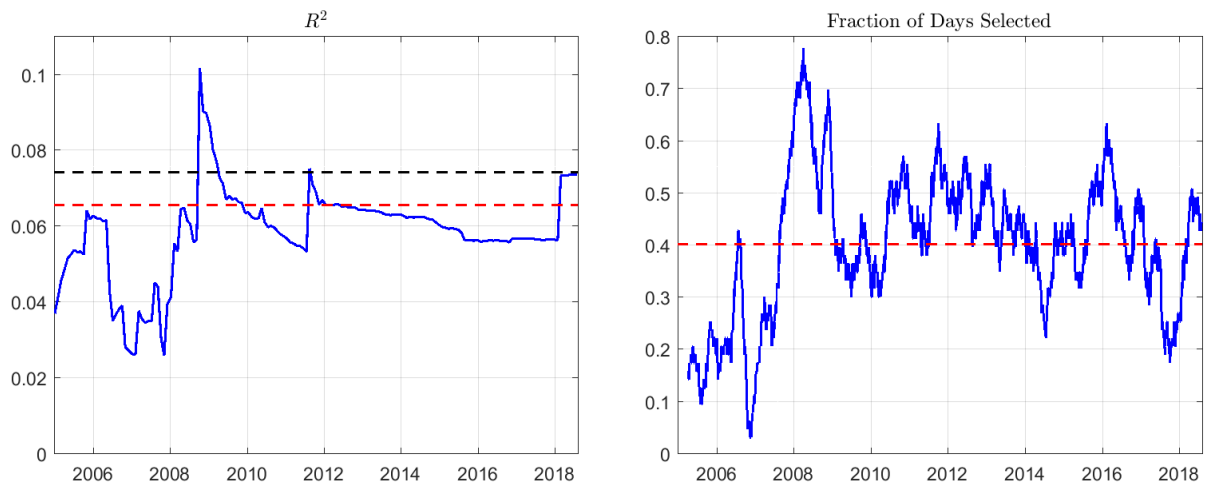


Figure IA.9

Market return on FOMC announcement days.

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

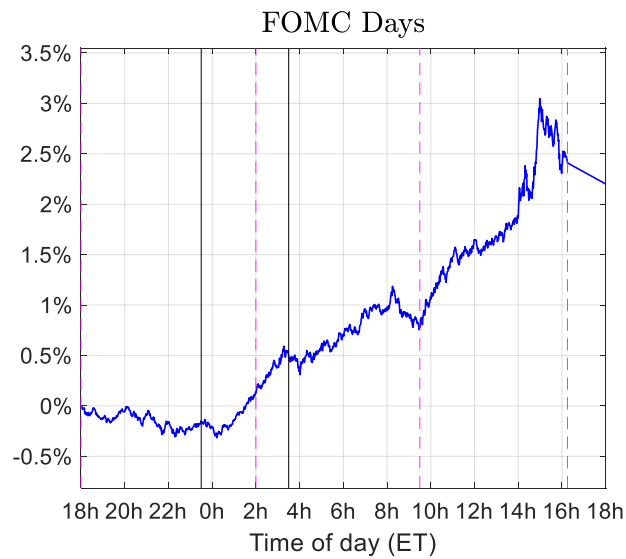


Figure IA.10

Cumulative VIX futures returns net of the leverage effect.

The figure shows how cumulative S&P-adjusted return for VIX futures varies over a day. We estimate beta of VIX futures with respect to the S&P E-mini return in a daily return regression. The two returns have a correlation of -0.85 (beta is -5.01) confirming a very strong leverage effect. We then adjust VIX futures returns to form a market-neutral strategy (VX-hedged). By construction, this strategy has zero correlation with S&P E-mini return at the daily frequency. Cumulative return is annualized by multiplying the period return by 252. Extended hours for VIX futures start spanning EU-open on June 22, 2014, and the sample ends in July 2018.

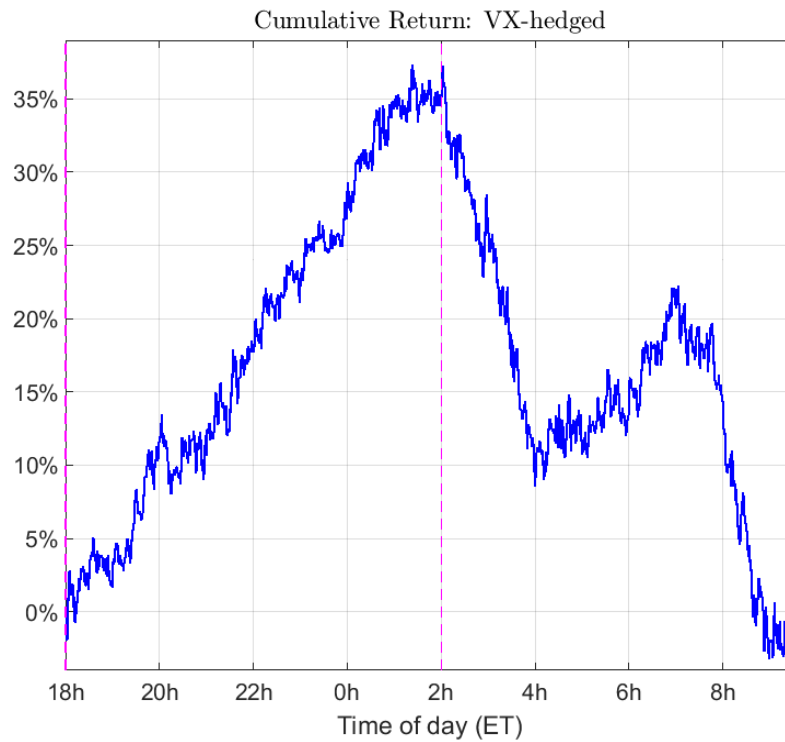


Figure IA.11

Variance ratio price efficiency test

This figure shows how the variance ratio depends on the time of the day. Higher ratio means less efficient prices. Variance at time t is computed as the average over all days of squared returns from t to $t+24h$. The figure shows the ratio of variance at time t to the overall daily average over all starting times. For example, the ratio of 1.08 at 0:00 means that variance is 8% higher than average for the 18:00-to-18:00 returns.

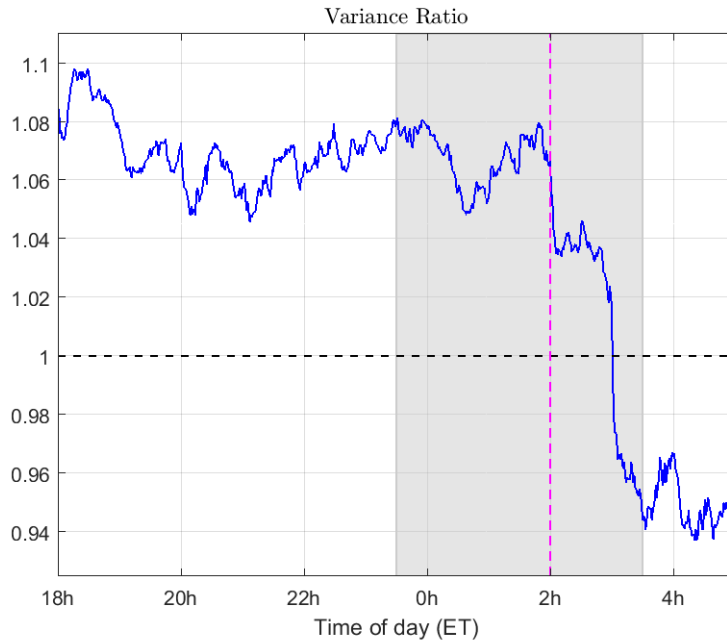


Figure IA.12
Weekends versus weekdays

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

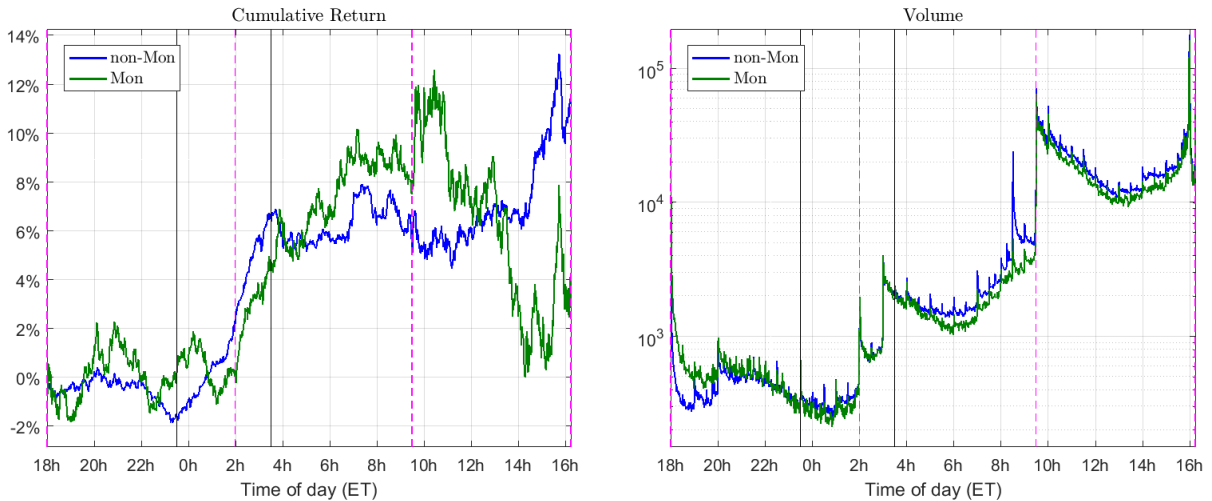


Figure IA.13
First and second part of the sample

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

