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Abstract

We analyze the transmission of monetary policy to the costs of hedging using options order book data. Monetary policy transmits to hedging costs both by changing the relevant state variables, such as the value of the underlying, its volatility and tail risk, and by affecting option market liquidity, including the bid-ask spread and market depth. Our estimates suggest that during the peak of the pandemic crisis in March 2020, monetary policy decisions resulted in substantial changes in hedging costs even within short intraday time windows around the decisions, amounting approximately to the annual expenses of a typical equity mutual fund.

Keywords

Liquidity, Monetary policy, Option order books, Option markets, COVID-19 pandemic.

JEL Classification

G13, G14, D52, E52.

1 Introduction

Over the past two decades, both the global financial crisis and the COVID-19 pandemic have triggered large fluctuations in asset prices. As investment and consumption tend to decline when firms and households face higher uninsured risks, the ability to hedge against such volatility—and the associated costs—are likely to play a significant role in mitigating the adverse macroeconomic effects resulting from such crises.[1] It remains a crucial open question, however, to which extent economic policy can foster cost-efficient insurance opportunities. In this work, we contribute to answering this question by analyzing how monetary policy decisions affect the ability to hedge equity market risks through option markets.

Option markets are an essential venue for risk sharing in developed economies, with millions of option contracts exchanged daily (see, e.g., Eurex). Their effectiveness in providing cost-efficient hedging opportunities depends primarily on two factors: the state variables governing option prices, particularly volatility and tail risk, and the liquidity of option markets. The transmission of monetary policy to hedging costs—defined here as the expenses incurred by a market participant seeking to insure a portfolio against stock market movements[2]—through these factors is thus a crucial element of the policy transmission channel.

A key aspect of our contribution to disentangling these two transmission channels lies in leveraging intraday information embedded in the limit order books of options on the EURO STOXX 50, a major European stock market index. These index options are widely used by institutional investors to hedge against aggregate crash risk (Bollen and Whaley, 2004, Johnson et al., 2016). Option order books are particularly valuable for this purpose because they serve as a venue for price discovery across multiple state variables. Unlike stock order books, which primarily reflect a firm's fundamental value, options incorporate additional state variables—such as volatility, upside and downside

[1] See, e.g., Dixit and Pindyck (1994) and Deaton (1993). In that literature, risk and uncertainty are used interchangeably and correspond to what we capture as 'volatility'. For a distinction between realized income shocks and volatility, see Dew-Becker et al. (2021).

[2] This notion of hedging costs should be distinguished from other forms, such as the replication costs faced by market makers as they continually adjust a replicating portfolio.

jump risks—that impact option prices alongside the underlying stock price. This exposes liquidity providers not only to inventory risk and transaction costs but also to informed trading on multiple state variables. Because the options' characteristics depend on their tenor and moneyness,[3] we can—guided by models from market microstructure (Foucault et al., 2013)—examine both channels jointly with minimal structural assumptions. This offers a significant advantage over previous studies that have investigated similar transmission aspects, often relying on monthly VAR estimates to assess the impact of monetary policy on volatility (Bekaert et al., 2013, Mumtaz and Theodoridis, 2020).

By analyzing option limit order book data from January to June 2020, we examine the impact of monetary policy interventions during a major crisis—an exemplary period when the availability of cost-efficient hedging opportunities is particularly critical. As a key finding, our analysis reveals the strong transmission of European Central Bank (ECB) and Federal Reserve (Fed) monetary policy decisions to the European equity option market, evident even within short intraday time windows around the announcements and particularly pronounced during the peak of the crisis. In our event analysis (see Table 9 for a summary), the monetary policy decisions on March 12, 15, 18, and 23, 2020, stand out. Quantitatively, the decisions on March 12 and 15 increased hedging costs by about 0.5% of the portfolio value for a portfolio insurance strategy, roughly equating to the annual expenses of a typical actively managed equity mutual fund. The substantial effects were primarily driven by changes in volatility, with tail risk playing a lesser role, and the impact of liquidity conditions being smaller and more nuanced.

These estimates, based on effects within narrow time windows around the decisions, capture only a portion of the overall increase in hedging costs implied by the sharp rise in volatility during the COVID-19 pandemic in March 2020, as illustrated in Figure 1 below. Nevertheless, with trading volumes in option markets increasing during the run-up to the pandemic and hedging costs against aggregate market risk rising simultaneously, they suggest significant potential for monetary policy to reduce hedging costs for market participants.

Our findings also indicate that monetary policy decisions have a heterogeneous effect

[3] See Bollerslev and Todorov (2011, 2014) and Andersen et al. (2015, 2020) for the relevant theory.

on the liquidity of options, potentially due to changes in information asymmetry about the states determining respective option prices. These findings connect to literature suggesting that asymmetric information—such as imperfectly observable collateral quality (Gorton and Ordoñez, 2014)—and deteriorating financial conditions can amplify adverse shocks, as highlighted in the financial accelerator literature (Bernanke et al., 1999).

Related literature

Methodologically, our high-frequency identification approach utilizes the unexpected component of the policy announcements as an exogenous shift to estimate the immediate intraday impact on option price state variables (underlying value, volatility, and tail risk) and liquidity measures (market depth, relative spreads). This builds on pioneering work by Cook and Hahn (1989), Kuttner (2001), Cochrane and Piazzesi (2002), and, more recently, Altavilla et al. (2019) and Badinger and Schima (2023) for the euro area. On the thematic side, we contribute to the rich literature on the impact of monetary policy on asset prices and related variables, including stock markets and market liquidity (Bernanke and Kuttner, 2005, Chordia et al., 2005, Lucca and Moench, 2015, Lagos and Zhang, 2020), uncertainty (Bekaert et al., 2013), inflation volatility (Mumtaz and Theodoridis, 2020), and corporate bond markets (Palazzo and Yamarthy, 2022).[4] Kargar et al. (2021), Haddad et al. (2021), and O'Hara and Zhou (2021) document major liquidity shortages in the U.S. corporate bond market during the COVID-19 pandemic and analyze how the Fed's monetary policy helped address them. Similarly, we observe an increase in spreads and an initial decline in market depth in option markets during the pandemic, with central bank decisions playing a role in reducing hedging costs. This is important, as option markets differ from the secondary corporate bond market in that they are organized through central clearing on an exchange and were not explicitly targeted by central bank interventions.

Monetary policy may transmit to asset markets by influencing expectations about the central bank's actions during times of crisis (e.g., Miller et al., 2002, Miller and Zhang,

[4]Bleich et al. (2013) and Gomez and Piccillo (2023) consider the reverse effect of uncertainty on monetary policy decisions.

2014). The expectations regarding the implicit insurance provided by central banks could be reflected in the pricing of options.[5] For example, using daily option data from 2008 to 2014, Hattori et al. (2016) show that the Fed effectively reduced tail risk, particularly when announcements of unconventional monetary policy included guidance on future interest rate paths. We contribute to this literature by analyzing the impact of monetary policy announcements during the COVID-19 crisis, using high-frequency data from option order books. These intraday data improve identification by enabling separate event analysis and allow us to distinguish between the volatility and tail-risk effects of monetary policy, as well as its influence on various dimensions of liquidity, such as the bid-ask spread and market depth—all of which affect hedging costs.

By focusing on option order books, we also contribute to the extensive empirical literature on market microstructure, which examines static and dynamic properties of limit order books for stocks (Biais et al., 1995, Sandås, 2001, Hollifield et al., 2004, Foucault et al., 2007, Christensen et al., 2013, Conrad et al., 2015). Unlike stocks, option order books are unique in simultaneously offering data on multiple order books for options on the same underlying asset, where options differ by strikes and tenors. As the first to analyze option order book data beyond the top-of-book level, we examine liquidity provision for options during the 2020 COVID-19 market crisis, an opportunity afforded by our specific sample period.[6]

2 Option markets and the COVID-19 shock

To set the stage for our analysis, we show in this section how the option market evolved during the sample period, with a specific emphasis on the EURO STOXX 50 index, its option-implied volatility, and other pertinent aspects of the market. It motivates why the sample period, which encompasses the first wave of the COVID-19 shock, is a key episode for analyzing the transmission of monetary policy to the cost of hedging. The descriptive evidence also contextualizes our intraday analysis of the monetary policy

[5] Hertrig and Zimmermann (2017) use option prices to assess the credibility of the Euro/Swiss Franc floor between 2011 and 2015.

[6] For stock market liquidity during the 2007/2008 financial crisis, see Rösch and Kaserer (2014).

events in Section 4.

The sample period covers the six months from 1 January 2020 to 30 June 2020. This provides a considerable dataset given the sheer volume of limit order book data and the complexity of processing such data, especially in comparison to the extant empirical literature on order books (Biais et al., 1995, Sandås, 2001, Hollifield et al., 2004).

2.1 Implied volatilities and systemic stress

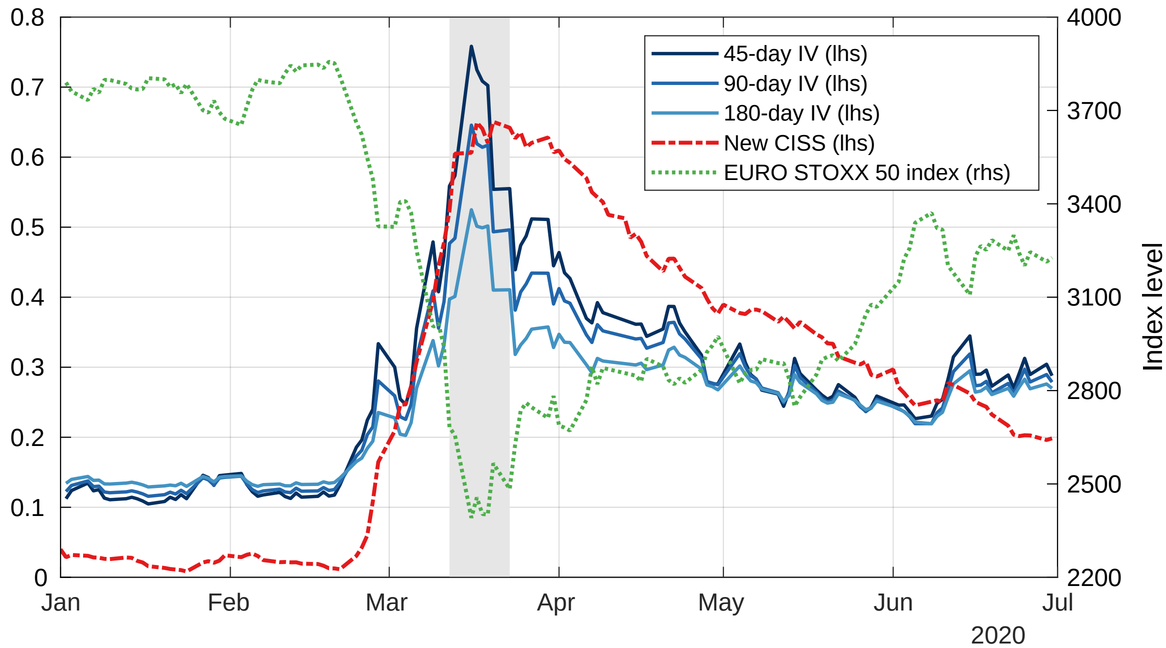
The COVID-19 pandemic led to substantial fluctuations in asset valuations and volatility. Differently from the global financial crisis, which originated endogenously from within the financial sector, the surge in volatility at the beginning of the pandemic was largely exogenous. The sample period therefore presents the opportunity to analyze the repercussions in the equity index option market, given its enormous relevance as a venue for risk sharing in the economy.

Figure 1 shows the EURO STOXX 50, its volatility implied by prices of options on the EURO STOXX 50 index (SX5E) with different times to expiry, together with the systemic-stress indicator (CISS) provided by the ECB.[7] The volatilities are averages of intraday Black-Scholes implied volatilities (IV).[8] The grey bar in Figure 1 represents the peak of the COVID-19 crisis in terms of market stress, for which we report results in the main text when we examine the impact of monetary policy decisions on option markets in Section 4 using intraday data.

Figure 1 reveals a strong positive correlation between the IVs and the systemic-stress indicator. At the same time, both variables exhibit an inverse relationship with the underlying asset, the EURO STOXX 50 index. The IVs and the stress indicator both peaked in mid March 2020, when the value of the EURO STOXX 50 hit the trough, and then remained at levels approximately three times higher than prior to the pandemic. Figure 1 also shows that the IV was slightly lower before the crisis for options with a

[7]The CISS is based on market-based financial stress measures such as realized volatilities and spreads covering money markets, bond markets, equity markets, financial intermediaries, and foreign exchange markets (Holló et al., 2012, Table 1).

[8]See Appendix C for further details on these calculations.



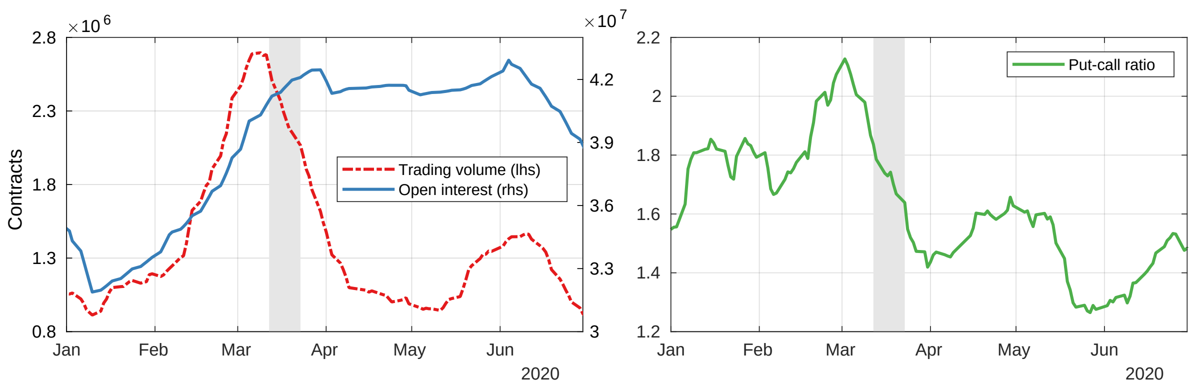
Sources: The new, unweighted measure of the CISS (Composite Indicator of Systemic Stress) is obtained from the ECB. Implied volatility is calculated based on option data provided by Eurex. *Notes:* Daily data. The grey bar indicates the time period from March 12 to 23, for which we report results in the main text when we analyze the effect of monetary policy decisions using intraday data in Section 4. In the figure, the implied volatilities are averages of implied volatilities calculated using intraday data for at-the-money put and call options, interpolated to the fixed tenors of 45, 90 and 180 days. Darker blue colors correspond to shorter tenors.

Figure 1: The EURO STOXX 50, its implied volatility and systemic stress.

short tenor, whereas during the crisis the term structure of IV inverted with short-dated options becoming more expensive (as measured in terms of IV) than long-dated options, consistent with widely documented stylized facts of IV (e.g., Fengler, 2011).

The large fluctuations in IV documented in Figure 1 imply huge price changes in options. Hence, insuring a well-diversified portfolio of European stocks with EURO STOXX 50 index options became massively more expensive in March 2020. Subsequently, the associated hedging costs declined until May 2020, reaching levels above those observed before the pandemic but significantly below the levels experienced at the peak of volatility in March 2020.

2.2 Trading volumes, open interest, and put-call ratio



Sources: Eurex. *Notes:* The put-call ratio, open interest, and the trading volume (number of contracts) refer to the entire EURO STOXX 50 option market traded on Eurex (on-book, off-book, including complex instruments, without any filtering on tenors or moneyness). All series represent monthly moving averages calculated from daily data. The grey bar indicates the time period from March 12 to 23, for which we report results in the main text when we analyze the effect of monetary policy decisions using intraday data in Section 4.

Figure 2: Trading volume, open interest, and put-call ratio

Figure 2 illustrates how the impact of the pandemic crisis is mirrored in the aggregate statistics of the total EURO STOXX 50 index option market on Eurex, including on-book and off-book data. The daily trading volume in the left panel (red dashed graph), measured by the number of traded contracts, almost tripled from about 1 MM contracts to close to 3 MM contracts between January and March 2020, suggesting that the EURO STOXX 50 index option market attracted a significant turnover at the same time as the massive increase in volatility, documented in Figure 1, increased the cost of hedging substantially.

The solid blue line in the left panel of Figure 2 provides insight into the open interest of the option market. Open interest represents the total number of outstanding contracts for a specific option that have not yet been settled. Unlike trading volume, open interest only increases when more new positions are opened than closed. The data show that open interest increased by approximately 30% between January and March 2020. This suggests that a significant number of new positions were created during this period, contributing to the substantial increase in trading volumes observed. As the grey bar indicates, a significant amount of option positions had already been created prior to the most volatile market phase in mid-March.

The put-call ratio in the right panel of Figure 2 illustrates the relative number of put and call options traded on a given day, calculated as the ratio of the purchased number of put options over the purchased number of call options. The figure reveals that the put-call ratio rose sharply to almost 1.8 in January, and then peaked at over 2 in early March 2020, coinciding with the outbreak of the pandemic in Europe. The high put-call ratio strongly suggests that the EURO STOXX 50 market played a crucial role in enabling risk-sharing among investors, especially for those who aimed to mitigate downward risks.

By April 2020, both the trading volume and put-call ratio significantly declined to nearly pre-crisis levels, indicating a reduction in market activity. Interestingly, open interest did not decrease at the same rate, implying that investors continued to maintain their market exposure even as trading subsided. Indeed, as shown by the grey bar in Figure 2, the trading volume and put-call ratio peaked just before the period, on which we put particular focus in our analysis of monetary policy decisions in Section 4. At the same time, the open interest continued to increase.

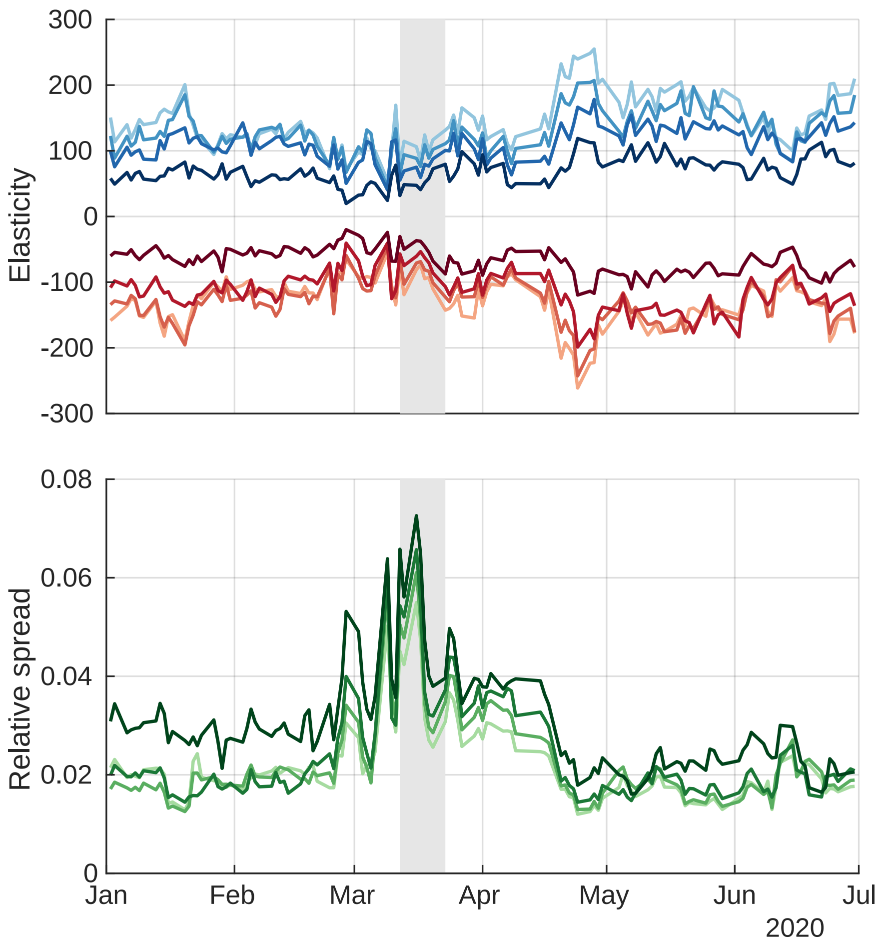
2.3 Option market liquidity

Figure 3 shows the evolution of the liquidity for put options with representative tenors in the interval of [121,365] days.[9] In the upper panel we show the evolution of market depth, and in the lower panel we report the relative spreads. To differentiate market depth and spreads within different moneyness buckets, we use darker colors to represent options that are further out of the money (OTM). Market depth is measured in terms of the quantity-price elasticity where the elasticity has a positive sign on the ask side and a negative sign on the bid side. As before, the grey bar indicates the time period from March 12 to 23.

The upper panel of Figure 3 illustrates that in January and February 2020, near-the-money options offered the highest market depth. At the onset of the COVID-19 crisis, spanning from late February to early March, market depth decreased across all strike ranges. As shown in the lower panel, the relative spreads nearly doubled. As of mid-March, market depth began to rebound. The relative spreads, however, continued their ascent and eventually tripled compared to pre-crisis levels, reaching their highest levels during this phase of heightened market stress. By the end of March, we observe a further recovery in market depth for all strike ranges, with elasticities returning to levels above or close to 100. Moreover, the spreads of near-the-money options, which had been much lower in January and February than spreads of far OTM options, converged, and declined to levels approximately 3/2 of their pre-crisis values. From April to May, the put market depth kept increasing, with the elasticity reaching levels near or even exceeding 200, and relative spreads receded further, mostly falling below 2%. Towards the end of the sample period in June, the overall elasticity remained persistently high and spreads relatively low.

Summarizing, rather than a straightforward liquidity contraction, the initial impact of the pandemic shock on option markets until mid-March was nuanced. Both compressions *and* expansions of liquidity occurred along the moneyness dimensions of the

[9] We provide a more extensive discussion of the evolution of option market liquidity, including put and call options with longer tenors, in Appendix E.2.



Sources: Eurex and own calculations. *Notes:* Daily data. Elasticities and spreads of puts with tenor in the interval of [121,365] days—see Sections B.2 and B.3 for computational details. The darker the color, the more out of the money (OTM) the option; the lighter the color, the more ITM the option. We classify the options based on the simple forward moneyness, defined as $\log(K/F^{\tau})$ where K is the strike, F the forward, and τ tenor. The buckets are [-0.3,-0.1], [-0.1,-0.05], [-0.05,0], [0,0.05]. The grey bar indicates the time period from March 12 to 23, for which we report results in the main text when we analyze the effect of monetary policy decisions using intraday data in Section 4.

Figure 3: Option market liquidity: the evolution of market depth and spreads over time

option price surface at times of the highest market distress. Additionally, it is worth noting that the days of very low market depth and high spreads in early March align with the periods of peak trading volume (refer to Figure 2), highlighting the importance of the EURO STOXX 50 index option market as a hedging venue. Conversely, during April and May, when liquidity was most favorable, the extraordinary turnover had already subsided.

Remarkably, over the entire sample period, the bid and the ask side evolved in almost perfect symmetry, suggesting that both the demand and supply of puts developed in lock-step. This differs from the findings of Haddad et al. (2021), Kargar et al. (2021), and O'Hara and Zhou (2021), who document a sharp rise of the selling pressure in the secondary corporate bond market and the unwillingness of dealers to supply liquidity.

3 The option order book data

To understand our analysis of the monetary policy transmission to the option market, it is instructive to describe the main features of the Eurex data on option order books. A more detailed description of the data, the construction of the variables, and a summary of the key stylized facts in Tables 6 and 7 are deferred to Appendices A to E.

Eurex is a futures exchange operated by Deutsche Börse AG in Frankfurt, Germany. The data we consider are derived from its order books of options on the EURO STOXX 50 index (OESX) and span over 124 trading days from January 1, 2020, to June 30, 2020.[10] The underlying asset, the EURO STOXX 50 index, is Europe's most widely recognized stock index. It is constructed from the 50 largest and most liquid stock corporations in the euro area, captures about 60% of the free-float market capitalization, and serves as an underlying asset for many financial products, such as futures and options (Qontigo, 2022). The trading venue for EURO STOXX 50 index futures and options offered by Eurex is among the most liquid derivative markets in Europe, also outside the euro area.[11]

[10] We exclude the trading days of April 14 and June 1. On April 14, an outage of the trading system occurred, and on June 1 (Whit Monday), German markets were closed, making the valuation of the underlying asset, the EURO STOXX 50 index, less reliable.

[11] According to the Derivatives Report of the World Federation of Exchanges, EURO STOXX 50 index options were the fifth most traded index option and the future on the EURO STOXX 50 index the world's

Over the sample period, the EURO STOXX 50 index option market totaled 29.7 MM traded contracts per month with an average monthly capital volume of 0.9 tn euro. The monthly open interest was 38.9 MM contracts (Eurex, 2020). The high trading intensity in these markets enables us to conduct intraday analyses of the order books for these options.

On Eurex, the OESX is traded in continuous limit order books with market makers operating from 9:00 to 17:30 hrs CET/CEST. Both limit and market orders can be placed. The order allocation method follows price-time priority. The contract size of the OESX is one, where one contract hedges the risk of 10 times the value of the underlying. The minimum tick size of OESX options is 0.1 index points. The OESX has cash settlement and is of European style. In our data set, we observe the five best quoted price levels on the bid and ask side of the order book, and trade information, like the execution price, quantity, and the aggressor side (bid or ask).

We apply filters to the order book and trade messages in the data to restrict the options considered for our analysis to a standardized moneyness range $[-6, 3]$, defined in Appendix E.1, and tenors between one to 365 calendar days. Moreover, we only consider observations made between 9:05 and 17:25 hrs as well as on-book trades and simple instruments (in contrast to complex instruments, which entail the trading of a bundle of options).

Table 4 in Appendix A provides summary statistics of the filtered data set. The trade statistics reveal that the order book is an important place for price discovery. More than half of the trading volume, whether measured in total daily euro trading volume or in daily traded contracts, is realized on-book. Specifically, the daily trading volume totals €159 MM and 237,000 contracts on-book versus €166 MM and 151,000 contracts off-book. Differences between trades on-book and off-book are larger in terms of the number of daily trades and the lot size per trade: there are 5,181 trades per day and 46 contracts per trade on-book versus 33 and 4,586 off-book. Thus, off-book trades are about 100 times larger than trades based on the order books where frequent but smaller sized trades are executed.

second most traded index future in 2020.

On average, the order books are frequently updated with approximately 470 updates per minute. The average relative spread between the best bid and ask price is 4.2% and the average quantity-price elasticity, estimated from the quantity-price schedules in the order books, is about 80 on the bid and ask side. A value of 80, for the elasticity of quantities with respect to price changes, implies an inverse elasticity of 1/80. A 100% increase in quantity then results in a 1.25% change in price.

4 Monetary policy transmission to option markets

Option prices are influenced by several state variables, most importantly volatility and tail risk.[12] However, their sensitivity to these variables depends strongly on the options' tenor and moneyness, which measures the distance between the strike prices and the current underlying asset price. More specifically, a short-dated at-the-money (ATM) option is to the largest extent influenced by the state of spot volatility (Medvedev and Scaillet, 2007, Durrleman, 2008). Conversely, short-dated far out-of-the-money (OTM) puts and calls, i.e., options with zero intrinsic value, reveal information about downside and upside jump risks but very little about volatility (Andersen et al., 2015, 2020).[13] As a consequence, unlike stock order books, which primarily reflect the stock's fundamental value, option order books expose liquidity providers to informed trading on both stock fundamentals and state variables like variance and jump risk.

In this section, we build on these insights to examine the extent to which monetary policy influences hedging costs in option markets. By carefully selecting the response variable, we differentiate the effects of monetary policy decisions on option prices—through volatility and upside and downside jump risks on the one hand, and through changes in option market liquidity on the other. To achieve credible identification, we exploit the unexpected component of monetary policy decisions at a high frequency in our data.

We conclude by providing an economic interpretation of the results, suggesting that

[12] We do not include the underlying asset here, as we focus on options with strike prices maintained in a constant relation to the underlying asset price, thereby eliminating this dependence.

[13] See Appendix D for illustrations and further intuition for these statements.

the analyzed monetary policy decisions may have influenced not only the state variables determining option prices but also the degree of information asymmetry about these state variables or the inventory risk faced by market makers.

4.1 Monetary policy decisions

Quiet periods at the ECB and the corresponding blackout periods at the Fed imply that monetary policy decisions potentially contain new information for option market participants. The decisions may transmit to option markets not only because they unexpectedly change the states that determine option prices but also because they affect uncertainty about the overall conditions of the economy and thus the liquidity in option markets.

The text of the monetary policy announcements and the press conferences after the monetary policy decisions provide clues concerning the new information and objectives of the decisions, where the scheduled time of the press releases and press conferences indicates precisely at which time of the day the information has become available. Following the narrative approach of analyzing monetary policy decisions (e.g., Badinger and Schima, 2023, Romer and Romer, 2023, and references therein), we show that the selected monetary policy decisions have impacted the state variables that determine option prices and thereby hedging costs, accidentally in some instances and less so in others.

We provide the full list of events we investigated in Appendix F.1. Table 9 in Appendix G.2 contains the results for all analyzed events. These include monetary and fiscal policy decisions as well as some other important incidents, both in the euro area and in the U.S. because economic policy decisions in the U.S. are known to be relevant for European markets (Ehrmann et al., 2011, Ca'Zorzi et al., 2020, Miranda-Agrippino and Rey, 2020, Jarociński, 2022). In the main text, we focus on four days of monetary policy decisions of the ECB and the Fed in March 2020 which stand out: the regular monetary policy meeting of the ECB on March 12 and its extraordinary meeting on March 18, 2020; and the extraordinary meetings of the Fed held on March 15 and March 23, 2020. As illustrated by the shaded area in Figure 1, these decisions bracket the peak of market volatility in mid-March.

On March 12, 2020, 13:45 hrs, the ECB announced measures related to longer-term refinancing operations (LTROs) and targeted longer-term refinancing operations (TLTRO III) to support bank liquidity conditions and thus bank lending, money market activity, and asset purchases. These measures were supposed to reduce liquidity risk, frictions in credit flow and financial excess sensitivity. In the subsequent press conference at 14:30 hrs, the ECB emphasized that the response to the COVID-19 pandemic had to be a (coordinated) fiscal response first and foremost to contain uncertainty. The statement "we are not here to close spreads," recorded at minute 43:37 of the press conference or in the relevant part of the transcript of the Q&A, was followed by a statement (included in the transcript) that the ECB remained "fully committed to avoid any fragmentation in a difficult moment for the euro area." As we are going to see below, this event is a good example for an event triggering higher volatility and tail risk as well as lower liquidity in option markets.[14]

The second monetary policy decision of the ECB – an emergency teleconference meeting – occurred after markets closed in the evening of March 18, 2020. The ECB then announced the €750 bn Pandemic Emergency Purchase Program (PEPP). The goal was to ensure transmission of monetary policy as documented in the minutes: "The situation was unprecedented and the repercussions were also impossible to forecast accurately. Uncertainty on the economic front was creating severe strains in the financial markets [...]. Faced with the risk of the ECB's monetary policy transmission becoming significantly impaired, there was an urgent need for the Governing Council to reassess its policy stance [...]." The quote highlights that the ECB reassessed its policy and accepted to play a more active role in complementing fiscal policy.

The two monetary policy decisions of the Fed, which we focus on, were taken on March 15 and March 23, 2020. On Sunday March 15 the Fed cut the policy rate by 100 basis points (bp) to 0-0.25% and announced quantitative easing measures with a volume of at least US $700 bn. During European trading hours on March 23, the Fed announced the primary and secondary market corporate credit facilities (PMCCF and SMCCF) to

[14] As acknowledged by Christine Lagarde, e.g., in the Financial Times on Oct 27, 2023, she did not anticipate such a market response to her initial statement.

provide credit to companies and improve liquidity in the secondary market for corporate bonds. The Fed also announced the term asset-backed securities loan facility (TALF) to sustain credit to consumers and businesses, and it extended the range of municipal securities that qualified for the commercial paper funding facility to sustain credit to municipalities. Finally, it promised to continue with asset purchases in the "amounts needed."

Haddad et al. (2021), Kargar et al. (2021), and O'Hara and Zhou (2021) have shown that the Fed's announcement on March 23 improved liquidity in U.S. bond markets, which had featured large spreads for investment grade bonds in mid-March. It is thus particularly interesting to see to which extent these decisions spilled over to the liquidity in European option markets and compare these effects to the Fed's earlier announcement on March 15, which applied more standard monetary policy instruments.

4.2 Econometric specification

In order to compare the observed patterns on usual trading days with those on an event day, we employ the following econometric specification for each event. We estimate it for each tenor and moneyness bucket at five-minute intervals t throughout all non-event days and the corresponding event within the sample period:

$$\begin{aligned} y_t = \alpha \quad &+ \quad \beta D_t^{(\mathrm{e})} + \sum_j \gamma_j D_t^{(\mathrm{e})} D_{jt}^{(45)} \\ &+ \quad \sum_i \delta_i D_{it}^{(5)} + \sum_d \delta_d D_{dt}^{(\mathrm{d})} + \sum_w \delta_w D_{wt}^{(\mathrm{w})} + \sum_m \delta_m D_{mt}^{(\mathrm{m})} + \kappa \log(\mathrm{tenor}) + u_t \ . \end{aligned} \tag{1}$$

Here $D_t^{(\bullet)}$ indicate time dummy variables. More specifically, $D_t^{(\mathrm{e})}$ is an event day dummy and $D_{it}^{(5)}$ assumes one if t falls into the ith 5-minute interval of the day. For example, a particular $D_{it}^{(5)}$ equals one in the time interval 10:00-10:05 hrs on all calendar days in the sample. Similarly, $D_{jt}^{(45)}$ equals one if t falls into the jth 45-minute interval of each trading day.[15] Analogously, $D_{dt}^{(\mathrm{d})}, D_{wt}^{(\mathrm{w})}$, or $D_{mt}^{(\mathrm{m})}$ take the value one if t is measured on

[15]The choice of 45 minutes is a compromise between accounting for the exact timing of the monetary policy announcement and press conference during the day and maintaining degrees of freedom in the estimation of the coefficients.

the dth weekday (e.g., a Monday), wth week of month (e.g., the first week of the month), or mth month of the year, respectively. Finally, u_t denotes the error term and log(tenor) controls for the time decay of options.[16]

We estimate the intraday effects γ_j using 45-minute intervals during the trading day, which enables us to exploit intraday variation for identification, similar to Andersen et al. (2017), Altavilla et al. (2019), Corsetti et al. (2021), and Gertler and Karadi (2015). To ensure that our estimates are not influenced by trading dynamics or illiquidity at the start of the trading day, we report effects beginning from 10:00 hrs onwards, where the interval 10:00-10:45 hrs on the event day is the benchmark interval in the estimations. We report the typical intraday patterns on non-event days in Appendix F.6. In robustness checks reported in Appendix G, we control for calendar weeks by interacting D_w and D_m.

The main coefficients of interest are the γ_j's that capture differences in the intraday patterns on the event day relative to non-event days. The sum $\alpha + \beta$ anchors the level of the dependent variable y_t at the beginning of the (first) event day relative to all non-event days in the sample and accounts, for example, for possibly different volatility or liquidity on event days as discussed in Lucca and Moench (2015).[17] For events that occurred between two calendar days, we have to consider event time windows which cover more than one day. We then replace $\beta\, D_t^{(e)}$ by $\beta_1\, D_t^{(e_1)} + \beta_2\, D_t^{(e_2)}$ and $\sum_j \gamma_j\, D_t^{(e)}\, D_{jt}^{(45)}$ by $\sum_j \gamma_{1j}\, D_t^{(e_1)}\, D_{jt}^{(45)} + \sum_j \gamma_{2j}\, D_t^{(e_2)}\, D_{jt}^{(45)}$. Then $\beta_2 - \beta_1$ captures the effect on the outcome variable which occurs between the first and second event day in the benchmark interval 10:00-10:45 hrs. The coefficient estimates for the γ_{1j}'s and γ_{2j}'s allow us to reconstruct the intraday effects on each of the two event days. The effects on a possible third event day are computed analogously.

As dependent variables in (1), we consider the log bid or ask option price, IV, the relative bid-ask spread, and market depth—see Sections B.2 and B.3 for the computational

[16]The time decay of options may be strong for very short-tenor options and could confound the effect of the event. The log parametrization is chosen because in the Black-Scholes model with an interest rate close to zero, the option price sensitivity to changes in tenor of an ATM option (the option theta) depends negatively on $\sqrt{\text{tenor}}$.

[17]The sample for each event we analyze differs slightly because it includes the non-event days and the day(s) for the respective event considered.

details. Given the standard notion that the underlying asset price follows a random walk, we do not estimate (1) using the value of the underlying as dependent variable. Instead, we report its log price difference vis-à-vis the benchmark time interval 10:00-10:45 hrs.

4.3 Results

Our empirical estimates show that monetary policy decisions during the pandemic changed the state variables determining option prices and that these changes may be, but do not need to be, associated with changes of liquidity in option markets. We report the results for all analyzed events in Table 9, Appendix G.2, and focus in the main text on four events which stand out.

The main results, reported in Table 1, are based on the comparison between a pre- and post-event window. Both windows are based on three 45-minute time intervals, i.e., a time window with a length of two hours and fifteen minutes. The pre-event window closes 45 minutes prior to the event, whereas the post-event window opens 45 minutes afterwards, ensuring that we account for market illiquidity in the immediate proximity of the event.[18] For the events that occur outside trading hours, the pre-event window contains the last three 45-minute intervals on the previous trading day and the first three 45-minute intervals on the following trading day.[19] Figures 11 and 13 in Appendix F.1 illustrate the intraday effects in more detail.

We focus on options with a tenor between 10 and 45 days to build on the insights concerning the informational content of short-dated options discussed in Appendix D. For the effects on the downside left-tail risk, we focus on put options further OTM with a standardized moneyness of −2.5 and a short tenor between one and seven days. For upside risk, we consider call options with such a short tenor and a standardized moneyness of 1.5.[20] The asymmetric standardized moneyness used for assessing downside

[18] The pre-event window on March 23 consists of only two 45-minute intervals because the event in the U.S. happened earlier in the European trading day. For the ECB announcement on March 12, the pre-event window closes 45 minutes before the announcement and the post-event window opens 45 minutes after the press conference.

[19] For the effect between March 18 and March 20 reported in Table 1, we compare the three 45-minute intervals on March 18 with the first three 45-minute intervals on March 20 after 10:00 hrs.

[20] Measures of tail risk may simultaneously utilize multiple OTM options (Andersen et al., 2017). Given

and upside risk reflects the asymmetry of the moneyness range in option order books discussed in Section E.1.

Table 1: The effect of monetary-policy events on option markets.

Panel A: Effect on the underlying asset, IV, and OTM option prices

				Tail risk			
				Put		Call	
Event date	Underlying level	IV 1-7 days	IV 45 days	Bid price	Ask price	Bid price	Ask price
March 12	−0.054	0.038	0.063	1.069	0.787	0.453	0.393
March 13/16	−0.085	0.366	0.162	−0.618	−0.219	0.551	0.779
March 18/19	−0.001	−0.001	−0.001	−0.026	0.056	−0.127	−0.071
March 18/20	0.078	−0.096	−0.164	−0.083	−0.052	−0.004	−0.025
March 23	0.018	−0.027	−0.033	−0.068	−0.138	−0.086	−0.052

Panel B: Effect on option market liquidity

	Relative spread				Elasticity							
	Put			Call	Put						Call	
	[−3, −2]	[−1, 0]	[0, 1]	[1, 2]	[−3, −2]		[−1, 0]		[0, 1]		[1, 2]	
Event date					Bid	Ask	Bid	Ask	Bid	Ask	Bid	Ask
March 12	0.037	0.021	0.016	−0.019	−16.4	−5.1	−60.3	−71.4	−15.5	−15.6	−0.6	−3.7
	(0.115)	(0.026)	(0.021)	(0.727)	(25.2)	(17.3)	(101.2)	(122.3)	(65.9)	(73.8)	(6.2)	(8.0)
March 13/16	0.061	0.000	0.012	0.124	0.0	1.8	47.7	34.3	−6.7	−22.3	−1.1	−0.8
	(0.125)	(0.045)	(0.032)	(0.695)	(8.4)	(7.7)	(34.5)	(45.5)	(50.2)	(63.0)	(5.5)	(6.8)
March 18/19	−0.002	−0.001	0.000	−0.055	−0.5	3.0	−37.3	−23.4	−4.7	2.1	0.7	−1.0
March 18/20	−0.029	−0.001	0.004	−0.145	13.7	−0.1	−24.4	3.5	6.1	13.9	0.4	−2.2
	(0.109)	(0.032)	(0.037)	(0.769)	(8.2)	(7.8)	(135.6)	(118.2)	(62.3)	(70.3)	(4.1)	(4.6)
March 23	0.012	0.005	0.001	0.063	−14.1	6.2	−56.2	−48.5	−43.3	−66.2	−4.9	−1.0
	(0.089)	(0.028)	(0.033)	(0.617)	(21.9)	(12.9)	(198.3)	(183.6)	(131.0)	(159.0)	(10.2)	(6.4)

Notes: The effects are highlighted with colors if they are statistically significant at the 5% level based on Newey-West standard errors (maximum lag is 15), except for the significance of the effect on the price of the underlying, for which we do not run regressions and simply test for significant differences of the price in the pre- and post-event window. The colors indicate the economic significance of the (statistically significant) effect, with more intense colors representing larger absolute changes. In Panel A, red means more turbulent markets with worse fundamentals (lower index valuation, higher IV, higher tail risk) and green suggests calmer markets with improved fundamentals. In Panel B, red represents lower liquidity (wider spreads, lower market depth), while green stands for higher liquidity (lower spreads, more market depth). In Panel B, the elasticities are presented as absolute values, so a negative coefficient indicates reduced market depth, and the level of the average elasticity or spread in the pre-announcement window is reported in parentheses. A value of 0.01 reported in the table implies a positive change of 1% if we consider the value of the underlying or the price of far OTM options in panel A, and a change of 1 percentage point if we consider the IV in panel A or the spread in panel B.

Table 1 shows that the analyzed monetary policy decisions had very distinct effects on option markets. We highlight entries with colors, if they are significant at a 5% level, with the color intensity representing economic significance. In Panel A, the color red indicates

that our data are constructed by averaging in five-minute intervals based on up to 60 order book snapshots, we are confident that our measurement is sufficiently robust for our purposes—see Section B.1.

more turbulent markets with worse fundamentals (lower index valuation, higher IV, higher tail risk) and green suggests calmer markets with improved fundamentals. A value of 0.01 reported in the table implies a positive change of 1% if we consider the value of the underlying or the price of far OTM options, and a change of 1 percentage point if we consider the IV or the spread.

Panel A of Table 1 shows that the ECB's decision on March 12 decreased the valuation of the underlying asset, increased IV for options with a short tenor (1-7 days or 10-45 days), and raised the tail risk on the downside and the upside, as both the price of OTM puts and calls increased massively. We convert the effect estimated in terms of the log option price into relative changes. Thus, the results reported in the table imply that the bid price of the OTM put increased by 107% and its ask price by 79%, within the short time window around the announcement on March 12. Similarly, OTM call prices soared by 39-45%. As the red colors suggests, these findings indicate that the ECB's announced LTROs and TLTROs, along with the subsequent communication during the press conference, did not meet the market's expectations and were ineffective in soothing market sentiment or diminishing risk.

The large policy rate cut and the quantitative easing announced by the Fed on March 15 had a similar effect: the stock price of the underlying dropped, volatility rose and more so for options with shorter tenor, consistent with the stronger increase of IV for options with shorter tenor documented in Figure 1. Differently to the effect of the ECB's decision on March 12, however, OTM put prices decreased, particularly so on the bid side, whereas OTM call prices increased. Given that we control for the time decay of options prices, a plausible interpretation of these observations is that although the announcement did not succeed in reducing uncertainty as reflected in the higher volatility state, it decreased the downside and increased the upside tail risk. Consequently, there may have been a shift towards a more balanced perception of upside and downside opportunities in the market.

Much in contrast, the subsequent two monetary policy decisions, i.e., the ECB's announcement of the PEPP on March 18 and the Fed's announcement of the corporate credit facilities (PMCCF and SMCCF) and the loan facility (TALF) on March 23, increased the EURO STOXX 50 index, reduced volatility and also some of the OTM option prices for puts and calls. This suggests that the monetary policy announcements also reduced downside and upside tail risk on these dates.[21]

Remarkably, the ECB's announcement in the evening of March 18, had no immediate impact on March 19 at all according to our analysis, neither on the underlying asset's valuation nor on the IV. Only the upside tail risk decreased slightly. We therefore also report the more substantial effects of the announcement on the subsequent day (March 20). This is because it appears possible that the effects of the announcement might have taken until March 20 to be fully reflected in prices. The ECB's decision was made after market closing on March 18, and its subsequent clarification occurred on March 19.[22]

Panel B of Table 1 reports the effects of the monetary policy decisions on option market liquidity, measured in terms of the relative spread and the quantity-price elasticity. The elasticity serves as a measure of market depth, with a large quantity-price elasticity $(\partial Q/\partial P)(P/Q)$ indicating deep markets because prices change *little* in the traded quantities. To benchmark the reported *changes* of the spread and elasticity, we report the values of the spread and and elasticity prior to the monetary policy decision in brackets below the respective estimated change. Note that the regression results are based on the absolute values of the quantity-price elasticity. Therefore, a negative effect indicates a

[21] We consider options with a tenor of 9 days on March 18 that have a tenor of 7 days on March 20. We observe put options for a standardized moneyness of -1 but not for -2.5 across all three event days. In robustness checks, we find similar results for the effect on downside tail risk between March 18 and 19 if we consider options with a tenor 2 days on March 18 and 1 day on March 19, for which we observe a standardized moneyness of -2.5. Moreover, we also obtain similar results for the effect on downside tail risk between March 19 and March 20 if we consider put options with a respective tenor of 8 and 7 days and a standardized of moneyness of -2.5. The effect on upside risk is less robust. If we consider call options with a tenor of two days on March 18 and one day on March 19, the results are less robust in the sense that upside risk increased rather than decreased. Furthermore, we also perform a robustness check controlling for the tenor when we compute the effect on the IV for options with a tenor between one and seven days. We find that the effect on the IV is quantitatively very similar to the results reported in Table 1. Only the negative effect on the IV for the event on March 18/20 becomes significantly larger in absolute terms with a value of -0.236 instead of -0.096.

[22] See the ECB blog, the interview of the ECB's executive board member Panetta, and the interview of the ECB's vice president de Guindos. As discussed further in Appendix F.1, the longer the considered time window after the event on March 18, the larger the possibility that other events also contributed to the effect estimated for March 20. It appears, however, unlikely that good news from the U.S. could have contributed to the positive trends in European markets. The day-to-day returns of the Dow Jones 30 Industrial on March 19 and March 20 were 0.94% and -4.65%, respectively, whereas the daily returns of the EURO STOXX 50 index were 2.82% and 3.78%.

decrease in market depth for both the bid and ask side. In Panel B, red indicates lower liquidity (wider spreads, lower market depth), whereas green indicates higher liquidity (lower spreads, more market depth).

Panel B of Table 1 shows that the ECB's monetary policy decision on March 12 reduced liquidity in option markets by increasing the spread and reducing market depth massively, as seen by inspecting the levels of the relative spreads and the market depth reported in brackets below the respective effects. The Fed's decisions on March 15 and March 23 had similar effects, with the exception of the increase in market depth for slightly OTM puts after the Fed's decision on March 15. Thus, although Panel A showed that the decision resulted in a higher volatility state, which strongly impacts near-the-money options, the liquidity for near-the-money puts improved quite strongly.

The ECB's PEPP decision on March 18 did not have a clear-cut immediate effect on liquidity on March 19, as suggested by the mixture of red and green colors visible in Panel B of Table 1 for that decision. It reduced only the spread for OTM calls and at the same time decreased market depth of slightly OTM puts substantially. Once we consider the time window until March 20, liquidity of far OTM put options increased in terms of lower relative spreads as well as more market depth (albeit from very low levels). Moreover, the decrease of market depth of slightly OTM puts is smaller if we consider the longer time window, suggesting that some of the effect measured on March 19 was only temporary. Thus, despite a significant reduction in the volatility level, market depth did not change in a clear-cut way after the central bank announcements. We provide an interpretation of these results in Section 4.4.

Quantitatively, the estimated effects of monetary policy decisions on the spread, reported in Panel B of Table 1, imply sizable changes of market liquidity, not only relative to the pre-event levels reported in brackets in Table 1 but also relative to the average values reported in Table 6. Furthermore, the percentage point increase in the relative spread is more pronounced for far OTM options, for which the spread is already larger to begin with. The effect on the elasticities appears to be less relevant. The reason is that the market for EURO STOXX 50 index options is very deep, as mentioned in stylized fact 7 of Appendix E.1. Thus, the elasticity changes, at least ATM, do not matter even if they are large compared to their pre-event levels because their price impact remains small. We analyze the quantitative implications of the elasticity changes further in Section 4.5 where we find that they do not matter quantitatively for the cost of hedging.

In Appendix G we show in Table 8 that controlling for calendar-week effects does not change our main findings. In Table 9, we also report results for other events which occurred during our sample period. For the other considered events, only the effect of the press release of the Fed on March 17 had an effect of similar magnitude as the events on which we focused in the main text. In the press release on March 17, the Fed announced the establishment of a commercial paper funding facility (CPFF) to provide liquidity to households and businesses. We find that this announcement reduced volatility, tail risk and hedging costs.

4.4 Interpretation

Through the lens of market microstructure models discussed in Appendix E.3, liquidity depends on asymmetric information or inventory risk and replication costs. More asymmetric information or larger inventory risk and replication costs increase spreads and reduce market depth, as measured by the price elasticity of option prices in the order book. We integrate these insights with those about the relationship between the sensitivity of short-dated option prices to changes of the state variables (volatility state and tail risk)—see Appendix D. This integrated approach allows us to further interpret the evidence presented in Panels A and B of Table 1, which show the effects of monetary policy decisions on the state variables as well as liquidity.

We start with interpreting the ECB's monetary policy meeting on March 12. Panel A of Table 1 shows that the unexpected component of the announcement reduced asset valuations, and increased expected volatility as well as tail risk. At the same time, option market liquidity decreased as shown in Panel B. These findings are consistent with both more information asymmetry about the state variables after the monetary decision or higher inventory risk, as higher volatility and tail risk may have increased the risk and expected hedging cost associated with holding option positions.

The Fed's decision on March 15 had more nuanced effects. Although volatility increased dramatically, liquidity deteriorated in the spread dimension but not in terms of market depth. Liquidity even improved in terms of more market depth for slightly OTM puts. These patterns suggest that asymmetric information about the volatility state decreased after the monetary policy decision. It is less evident how a model of inventory risk and replication costs of market makers could explain the increased market liquidity in slightly OTM puts along with heightened volatility. This is because the underlying asset is expected to fluctuate more at elevated volatility levels, requiring more frequent revisions of the replicating portfolio. Similarly, the findings in Panels A and B indicate an increase in asymmetric information concerning downside risk after the Fed's decision on March 15. This is suggested by the wider spreads of far OTM puts within the standardized moneyness range of $[-3, -2]$ although the price of these puts declined indicating less downside risk. In contrast, inventory risk as well as asymmetric information may explain the observed patterns for OTM calls because both upside risk and spreads increased.

Turning to the ECB's PEPP decision of March 18, we have found that the event had no effect on the state of volatility and downside tail risk on March 19 but reduced the market depth for slightly OTM puts. This suggests that changes in information asymmetry about volatility may have caused the changes in market liquidity for puts on March 19. It is unclear how inventory risk or replication costs of market makers could have contributed to the observed liquidity effects, given the absence of any observed changes in the state variables that govern these option prices.[23] If we include March 20 into the event window, we observe a decrease of volatility after the ECB's PEPP decision, and no change in the tail risk instead. The effect on market liquidity on March 20 is less clear cut and difficult to interpret because of the heterogeneity of the effects.

The Fed's decision on March 23, had only a small effect on the state variables but reduced market liquidity both in terms of spreads and market depth. Building upon our

[23]In Panel B of Table 1, we also observe a relatively smaller spread and a larger elasticity for OTM calls after the ECB's PEPP decision. Although these changes are statistically significant, they are quite small in absolute terms when compared to the liquidity levels before the ECB's decision (as indicated within brackets). Therefore, we do not interpret them further.

previous arguments, this indicates an increase in asymmetric information subsequent to the Fed's decision rather than a change in inventory risk or replication costs of market makers.

To sum up, the monetary policy decisions of the ECB on March 18 and the Fed on March 23 helped reduce the cost of hedging risks in option markets, mainly by slashing volatility levels. The effect on hedging costs resulting from the changes of market liquidity are less clear cut. The elasticity and spreads both increased and decreased depending on the option characteristics after the ECB's decision on March 18 whereas market liquidity decreased more uniformly after the Fed's decision on March 23. An interpretation is that more information asymmetry has been associated with the announcement of the non-standard measures on March 23 which may have reduced market liquidity.

Taken together, these results demonstrate that monetary policy decisions affect the costs associated with hedging risks, both by changing the states that determine option prices and by changing market liquidity. Changes in market liquidity can arise because monetary policy decisions change the informativeness of trades or the inventory risk of market makers.[24] We quantitatively measure this impact in the next subsection.

4.5 The transmission of monetary policy to the cost of hedging

Monetary policy can stabilize or destabilize the economy through its effects on option markets, as the cost of hedging plays a crucial role in determining the prices at which financial intermediaries, firms, and households can reduce risk. Consequently, we now analyze the transmission of monetary policy to the cost of hedging in further detail.

The results of our analysis indicate that the monetary policy decisions made on March 18 and 23 contributed to a decrease in volatility, which in turn led to lower hedging costs. Conversely, the decisions made on March 12 and 15 had the opposite effect. We now provide two quantitative illustrations based on the estimates of Table 1. We first illustrate the effect of the events on hedging costs caused by changes in volatility on the

[24] This is in line with literature on endogenous market incompleteness, suggesting that the cost and availability of risk sharing in private insurance markets depend on asymmetric information due to adverse selection (e.g., Golosov and Tsyvinski, 2007), moral hazard and transaction costs (e.g., Bertola and Koeniger, 2015), or limited commitment (e.g., Krueger and Perri, 2006).

one hand and by changes in option market liquidity on the other hand. Concerning liquidity, we distinguish the effects induced by the spread and market depth. In a second step, we illustrate the full effect on hedging costs caused by changes of option prices and market liquidity. The quantitative illustrations have to be taken with a grain of salt, of course, and should not be misunderstood to imply that public equity funds, e.g., may want to engage in the hedging activities we assume for our illustrations.

4.5.1 The effect on hedging costs through changes in volatility and market liquidity

For the first illustration, we focus on slightly OTM put options with a tenor between 10 and 45 days to provide a quantitative interpretation of the estimates reported in Table 1. Our analysis aims to decompose the effect of the monetary policy event on hedging costs into two components: changes in volatility and changes in liquidity.

To approximate the first component, we use the estimated volatility effect reported in Table 1 together with the option price sensitivity to volatility changes, i.e., the option vega, in the pre-event window. For simplicity, we use the Black-Scholes (BS) formula for that purpose. We multiply the BS vega with the change of IV for an ATM option with a tenor of 45 days, assuming that the price change applies symmetrically to the bid and ask price. To illustrate the change in hedging costs in euro, we consider a portfolio worth 1 MM euro with the same systematic risk as the EURO STOXX 50 index (i.e., with a beta of one), which shall be hedged by purchasing ATM put options.[25]

Concerning the additional effect ensuing from changes in liquidity, we use the estimated effect of the event on the spread reported in Table 1 and attribute half of the change of the spread to the bid and ask side, respectively. We calculate the implied price change by multiplying half of the spread's change with the bid and ask price in the pre-event window. To obtain the consolidated price change, we weigh the price change on the bid and ask sides by the respective share of the trade value in euro on each side of the market in the sample.

In addition, we incorporate changes in the price-quantity schedule in the order book,

[25]Because each option contract hedges the risk of 10 times the value of the underlying, the number of contracts for computing the change of hedging costs is 1 MM / (10×price of the underlying in the pre-event window), where the strike price equals the value of the underlying for ATM options.

which are implied by the estimated change in elasticity, to calculate the change in the hedging cost resulting from purchasing the necessary number of option contracts to hedge a 1 MM euro portfolio (see Appendix B.4 for details). Given that the changes of the elasticities have a negligible effect on the hedging costs, we will omit them from the subsequent discussion.

Table 2: The effect on hedging costs through changes in volatility and liquidity.

	IV		Relative spread		Elasticity	
Event date	Change in euro	Change in %	Change in euro	Change in %	Change in euro	Change in %
March 12	8,106	19.7	406	1.0	0.33	0.03
March 13/16	22,339	39.8	1	0.0	−0.35	−0.03
March 18/19	−128	−0.2	−35	−0.1	0.07	0.01
March 18/20	−19,596	−32.3	−22	0.0	0.02	0.00
March 23	−4,532	−9.8	100	0.3	0.05	0.01

Notes: The table shows the effect of the respective event on option prices and hedging costs because of changes in the implied volatility, spread and elasticity estimated in Table 1. The color scheme is analogous to Table 1 with red illustrating higher hedging costs and green lower hedging costs. The intensity of the color indicates the economic significance of the (statistically significant) effect, where the standard errors are obtained from the estimations reported in Table 1 applying the delta method. The table reports the changes in percent and in euro. For the effect of the respective event on the euro value of hedging costs, we assume a portfolio of 1 MM euro to be hedged by purchasing ATM options, for which the strike price equals the value of the underlying. Because each option contract hedges the risk of 10 times the value of the underlying, the number of contracts for computing the change of hedging costs is then 1 MM / (10×price of the underlying in the pre-event window). The change of the hedging costs attributed to volatility is expressed in percent of the value of put options slightly OTM with a standardized moneyness of −0.5. For the spreads and elasticities, the change of the hedging costs in percent is expressed in percent of the price of slightly OTM put options at the respective event date. Thus, the same change in absolute cost may result in different percentage changes across event dates because the price of slightly OTM put options differs across event dates. The change of the hedging costs attributed to the relative spread is also expressed in percent of the price of slightly OTM put options, for which results are reported in Table 1.

As shown in Table 2, the largest proportion of changes in hedging cost needs to be attributed to the effect of the events on the volatility state. Indeed, the price effect accounted for by changes in the spread are at least an order of magnitude smaller. For instance, the monetary policy decision on March 12 by the ECB resulted in a 19.7% increase in the cost of hedging (equivalent to 8,106 euro for a portfolio worth 1 MM euro) because of the increase in volatility, and a 1% increase in the cost of hedging (equivalent to 406 euro for a portfolio worth 1 MM euro) because of the increase of the spread. We find an even more sizable effect on hedging costs through volatility changes for the decisions in the event windows March 13/16 and March 18/20.

4.5.2 The full effect of monetary policy on hedging cost

We now assess the effect of the monetary policy events on hedging costs more comprehensively and consider all direct effects of the event on option prices (not only through changes in IV and market liquidity). To this end, we also include put and call options with a longer tenor in the standardized moneyness intervals of $[-1, 0]$ for puts and $[0, 1]$ for calls, because they account for most of the euro trading volume.

Table 3: The effect of monetary policy on hedging costs.

	Tenor					
	[10, 365]		[10, 45]	[46, 80]	[81, 120]	[121, 365]
Event date	Change in euro	Change in %	Change in %	Change in %	Change in %	Change in %
March 12	5,671	15.2	17.8	15.4	12.9	9.6
	(100)	(100)	(100)	(100)	(100)	(100)
	{100}	{100}	{100}	{100}	{100}	{100}
March 13/16	8,463	18.4	23.6	15.7	14.2	10.0
	(97)	(97)	(100)	(100)	(100)	(94)
	{100}	{100}	{100}	{100}	{100}	{100}
March 18/19	405	0.9	1.2	1.1	0.2	0.1
	(7)	(7)	(0)	(0)	(0)	(17)
	{50}	{50}	{0}	{0}	{0}	{50}
March 18/20	−9,977	−21.0	−23.6	−22.0	−18.6	−14.8
	(100)	(100)	(100)	(100)	(100)	(100)
	{0}	{0}	{0}	{0}	{0}	{0}
March 23	−3,509	−8.9	−6.2	−10.2	−12.6	−12.1
	(100)	(100)	(100)	(100)	(100)	(100)
	{0}	{0}	{0}	{0}	{0}	{0}

Notes: For the effect of the respective event on the euro value of hedging costs, we assume a portfolio of 1 MM euro to be hedged by purchasing ATM options, for which the strike price equals the value of the underlying. Because each option contract hedges the risk of 10 times the value of the underlying, the number of contracts for computing the change of hedging costs is then 1 MM / (10×price of the underlying in the pre-event window). The change of the hedging costs in percent is expressed in percent of the price of slightly OTM put options at the respective event date. The days delimiting the respective tenor bucket in the table are in square brackets in the respective column header. Below the change in euro or percent in each cell, we report the (percentage of regressions with a price effect significant at the 5% level) and the {percentage of regressions with a positive price effect significant at the 5% level}. The effect reported for each event window is based on regressions on the bid and ask side for puts and calls with different tenors. The effect reported in each cell is consolidated weighing the changes across tenor buckets, the bid and ask side in each bucket, and the type of option (put or call), using the pre-event values of the respective traded volume as weights.

Table 3 summarizes the results. For the consolidated changes of the hedging cost, reported in the first and second column, we weigh the changes across tenor buckets, the bid and ask side in each bucket, and the type of option (put or call), using the respective trading volume in the sample as weight. In the last four columns, we also report the changes per tenor because we find some heterogeneity of the effects on hedging costs across tenor buckets but the effects do not differ much between the bid and ask side and between calls and puts.

Table 3 shows that the monetary policy decisions made on March 12 and 15 resulted in a 15% and 18% increase in hedging costs, corresponding to additional expenses of 5,671 euro and 8,463 euro respectively for hedging the risk of the 1 MM euro EURO STOXX 50 portfolio. The monetary policy decisions on March 12 and 15 thus increased hedging costs at least 0.5% of the portfolio value. Conversely, the subsequent decisions on March 18 and 23 led to a reduction in hedging costs. The quantitative effect was a bit larger between March 18 and March 20 resulting in a decrease of 9,977 euro. On March 23, hedging costs decreased by 3,509 euro.

The effect of monetary policy decisions on hedging costs in March 2020 are sizable quantitatively. To put them into perspective, we compare them with annual expense ratios of typical funds. As a lower bound for the expense ratio, we consider a typical index fund for the EURO STOXX 50 which has a portfolio of 5,000 MM euro and an expense ratio of 0.1%.[26] If portfolios of this size had to be hedged, the estimated changes of hedging costs in Table 3 would imply a cost increase of 28 and 42 MM euro after the monetary policy decisions on March 12 and 15 and a decrease of 50 and 17 MM euro after the monetary policy decisions on March 18 and 23. These changes of hedging costs amount to 0.35% and 1% of the value of the portfolio. They are thus 3.5-10 times larger than the annual expense ratio of 0.1% of such an index fund. If we consider the expense ratios of typical *actively* managed funds instead, which are approximately 10 times larger than for passively managed funds, the changes of the hedging cost can easily amount to the annual expenses of such funds.[27]

Qualitatively, the results mirror those reported in Table 1 for the effect of monetary policy decisions on volatility. This is not surprising because prices of slightly OTM options are particularly sensitive to volatility changes (Appendix D). Concerning the heterogeneity across tenors, we find that hedging costs changed relatively more after

[26] See, for example, iShares Core EURO STOXX 50 UCITS ETF or Euro Stoxx 50 UCITS ETF 1D, accessed on April 18, 2023.

[27] See the documentation of average expense ratios by the Investment Company Institute.

the decisions on March 12, 15, and 18 for options with shorter tenor. In contrast, they decreased relatively more for longer tenors after the decision on March 23. This suggests that the Fed's monetary policy decision on March 23 mattered relatively more for market expectations over longer horizons. Whereas the ECB's PEPP decision on March 18/20 had a strong effect on markets both in the short term and long term, the Fed's PMCCF and SMCCF programs announced on March 23 played a crucial role in stabilizing markets in the long term, in line with the large associated reductions in the IV visible in Figure 1.

It is insightful to compare the effect of monetary policy decisions on hedging costs if OTM options rather than ATM options were used for hedging. This would reduce the cost of hedging, because OTM options are cheaper as they imply a possible loss at expiry. For instance, focusing on OTM put options with a standardized moneyness of −2.5, which account for about 1.7% of the volume of traded options in our sample, we find that the ECB's policy decision on March 12 increased the price of these far OTM options by 27% but the cost of hedging against extreme downside risk only by 1,189 euro for a portfolio worth 1 MM euro (consolidated across tenor buckets and the bid and ask side as before). As shown in Table 3, the corresponding effects for slightly OTM/ATM options are 15% and 5,671 euro.[28] Because they only provide a hedge against extreme events, far OTM options have significantly lower prices. Consequently, this leads to larger price changes in percentage terms but smaller changes in euro terms compared to options closer to the money. This comparison highlights that the effect of monetary policy decisions on hedging costs in euro are dominated by options that are near-the-money, not only because their trading volume is the highest, but also because they are more costly in the first place.

[28]The effect reported in Table 3 includes both puts and calls. Because the effects are very similar across put and call options, the different effects on hedging costs, if OTM rather than ATM options were used for hedging, do not result from the focus on OTM put options for this comparison.

5 Conclusion

We have analyzed the transmission of monetary policy to the prices and liquidity of a leading European option trading venue, the market of EURO STOXX 50 index options. In doing so, we have produced stylized facts for this market, using high-frequency data on option order books. We have illustrated differences in liquidity between put and call options with different tenor and moneyness. Based on the intraday data, we have shown that monetary policy decisions transmit significantly to the hedging costs in option markets, both by changing the state variables that determine option prices and by affecting liquidity provision in the option market.

Our estimates imply that the monetary policy decisions on March 12 and 15 during the pandemic crisis increased the hedging costs by an amount approximately equal to the annual expenses of actively managed funds. In contrast, the decisions on March 18 and 23, decreased the hedging cost by a similar amount.

We have found that the transmission of monetary policy to the cost of hedging during the pandemic has been mostly through changes of the state variables determining option prices rather than through changes of option market liquidity. Among the state variables, the transmission of monetary policy to volatility has been most important quantitatively for the cost of hedging, both because the effects of monetary policy decisions on volatility have been large and because options slightly OTM, whose price covaries strongly with volatility, account for most of the trading volume in option markets.

Our findings show that certain monetary policy decisions during the pandemic helped mitigate the crisis by reducing market volatility and thus also the cost of hedging. There appears to be potential for monetary policy to enhance option market liquidity through more targeted monetary policy measures and, as a result, decrease the cost of hedging for a given market volatility. Whether this is desirable from a welfare perspective, is unclear, however, because of informational asymmetries in option markets.

The spread and the elasticity of option prices with respect to traded quantities are possible indicators for trade informativeness. Future research thus could explore how the spreads and elasticities, which we have estimated, compare to their socially optimal counterparts in a structural model environment. Another fruitful avenue for further investigation would be to explore how monetary policy transmission propagates farther into the real economy by examining the real effects on consumption or investment arising from the changes in hedging cost estimated in this paper.

References

Altavilla, C., Brugnolini, L., Gürkaynak, R. S., Motto, R., and Ragusa, G. (2019). Measuring Euro Area Monetary Policy. *Journal of Monetary Economics*, 108(C):162–179.

Amihud, Y. and Mendelson, H. (1980). Dealership Market: Market-Making with Inventory. *Journal of Financial Economics*, 8(1):31–53.

Andersen, T. G., Archakov, I., Grund, L., Hautsch, N., Li, Y., Nasekin, S., Nolte, I., Pham, M. C., Taylor, S., and Todorov, V. (2021). A Descriptive Study of High-Frequency Trade and Quote Option Data. *Journal of Financial Econometrics*, 19(1):128–177.

Andersen, T. G., Fusari, N., and Todorov, V. (2015). The Risk Premia Embedded in Index Options. *Journal of Financial Economics*, 117(3):558–584.

Andersen, T. G., Fusari, N., and Todorov, V. (2017). Short-Term Market Risks Implied by Weekly Options. *The Journal of Finance*, 72(3):1335–1386.

Andersen, T. G., Fusari, N., and Todorov, V. (2020). The Pricing of Tail Risk and the Equity Premium: Evidence from International Option Markets. *Journal of Business & Economic Statistics*, 38(3):662–678.

Audrino, F. and Fengler, M. (2015). Are Classical Option Pricing Models Consistent with Observed Option Second-Order Moments? Evidence from High-Frequency Data. *Journal of Banking and Finance*, 61:46–63.

Badinger, H. and Schima, S. (2023). Measuring Monetary Policy in the Euro Area Using SVARs with Residual Restrictions. *American Economic Journal: Macroeconomics*, 15(2):279–305.

Battalio, R. and Schultz, P. (2011). Regulatory Uncertainty and Market Liquidity: The 2008 Short Sale Ban's Impact on Equity Option Markets. *The Journal of Finance*, 66(6):2013–2053.

Bekaert, G., Hoerova, M., and Lo Duca, M. (2013). Risk, Uncertainty and Monetary Policy. *Journal of Monetary Economics*, 60:771–788.

Bernales, A., Verousis, T., Voukelatos, N., and Zhang, M. (2020). What Do We Know About Individual Equity Options? *Journal of Futures Markets*, 40(1):67–91.

Bernanke, B. S., Gertler, M., and Gilchrist, S. (1999). The Financial Accelerator in a Quantitative Business Cycle Framework. In Taylor, J. B. and Woodford, M., editors, *Handbook of Macroeconomics*, volume 1C, chapter 21, pages 1341–1393. Elsevier.

Bernanke, B. S. and Kuttner, K. N. (2005). What Explains the Stock Market's Reaction to Federal Reserve Policy? *The Journal of Finance*, 60(3):1221–1257.

Bertola, G. and Koeniger, W. (2015). Hidden Insurance in a Moral-Hazard Economy. *RAND Journal of Economics*, 46(4):777–790.

Biais, B., Hillion, P., and Spatt, C. (1995). An Empirical Analysis of the Limit Order Book and the Order Flow in the Paris Bourse. *Journal of Finance*, 50(5):1655–1689.

Bleich, D., Fendel, R., and Rülke, J.-C. (2013). Monetary Policy and Stock Market Volatility. *Economics Bulletin*, 33(3):1669–1680.

Bollen, N. P. and Whaley, R. E. (2004). Does Net Buying Pressure Affect the Shape of Implied Volatility Functions? *The Journal of Finance*, 59(2):711–753.

Bollerslev, T. and Todorov, V. (2011). Tails, Fears, and Risk Premia. *The Journal of Finance*, 66(6):2165–2211.

Bollerslev, T. and Todorov, V. (2014). Time-Varying Jump Tails. *Journal of Econometrics*, 183(2):168–180.

Ca'Zorzi, M., Dedola, L., Georgiadis, G., Jarociński, M., Stracca, L., and Strasser, G. (2020). Monetary Policy and its Transmission in a Globalised World. ECB Discussion Papers No. 2407, ECB, Frankfurt.

Cenesizoglu, T. and Grass, G. (2018). Bid- and Ask-Side Liquidity in the NYSE Limit Order Book. *Journal of Financial Markets*, 38:14–38.

Chakravarty, S., Gulen, H., and Mayhew, S. (2004). Informed Trading in Stock and Option Markets. *The Journal of Finance*, 59(3):1235–1257.

Chen, C. Y.-H., Fengler, M. R., Härdle, W. K., and Liu, Y. (2022). Media-Expressed Tone, Option Characteristics, and Stock Return Predictability. *Journal of Economic Dynamics and Control*, 134:104290.

Chordia, T., Sarkar, A., and Subrahmanyam, A. (2005). An Empirical Analysis of Stock and Bond Market Liquidity. *Review of Financial Studies*, 18(1):85–129.

Christensen, H. L., Turner, R. E., Hill, S. I., and Godsill, S. J. (2013). Rebuilding the Limit Order Book: Sequential Bayesian Inference on Hidden States. *Quantitative Finance*, 13(11):1779–1799.

Christoffersen, P., Goyenko, R., Jacobs, K., and Karoui, M. (2018). Illiquidity Premia in the Equity Options Market. *The Review of Financial Studies*, 31(3):811–851.

Cochrane, J. H. and Piazzesi, M. (2002). The Fed and Interest Rates - A High-Frequency Identification. *American Economic Review*, 92(2):90–95.

Conrad, J., Wahal, S., and Xiang, J. (2015). High-Frequency Quoting, Trading, and the Efficiency of Prices. *Journal of Financial Economics*, 116(2):271–291.

Cook, T. and Hahn, T. (1989). The Effect of Changes in the Federal Funds Rate Target on Market Interest Rates in the 1970s. *Journal of Monetary Economics*, 24(3):331–351.

Corsetti, G., Duarte, J. B., and Mann, S. (2021). One Money, Many Markets: Monetary Transmission and Housing Financing in the Euro Area. *Journal of the European Economic Association*.

Deaton, A. (1993). *Understanding Consumption*. Oxford University Press.

Deutsche Börse Group (2019). Functional Reference, T7 Release 8.0. https://www.eurex.com/ex-en/support/initiatives/archive/release8/Overview-and-Functionality-1546132. [Online; accessed 12-08-2022].

Deutsche Börse Group (2020). Market and Reference Data Interfaces, T7 Release 8.0. https://www.eurex.com/ex-en/support/initiatives/archive/release8/Market-and-Reference-Data-Interfaces-1546120. [Online; accessed 12-08-2022].

Dew-Becker, I., Giglio, S., and Kelly, B. (2021). Hedging Macroeconomic and Financial Uncertainty and Volatility. *Journal of Financial Economics*, 142(1):23–45.

Dierker, M., Kim, J.-W., Lee, J., and Morck, R. (2016). Investors' Interacting Demand and Supply Curves for Common Stocks. *Review of Finance*, 20(4):1517–1547.

Dixit, A. K. and Pindyck, R. S. (1994). *Investment under Uncertainty*. Princeton University Press.

Duffie, D., Pan, J., and Singleton, K. (2000). Transform Analysis and Asset Pricing for Affine Jump-Diffusions. *Econometrica*, 68(6):1343–1376.

Durrleman, V. (2008). Convergence of At-The-Money Implied Volatilities to the Spot Volatility. *Journal of Applied Probability*, 45(2):542–550.

Ehrmann, M., Fratzscher, M., and Rigobon, R. (2011). Stocks, Bonds, Money Markets and Exchange Rates: Measuring International Financial Transmission. *Journal of Applied Econometrics*, 26:948–974.

Eurex (2020). Eurex Monthly Statistics, July. https://www.eurex.com/ex-de/marktdaten/statistik/monatsstatistiken. [Online; accessed March-04-2022].

Fengler, M. R. (2011). Option Data and Modeling BSM Implied Volatility. In Duan, J. C., Gentle, J. E., and Härdle, W., editors, *Handbook of Computational Finance*. Springer-Verlag, Berlin.

Foucault, T. (1999). Order Flow Composition and Trading Costs in a Dynamic Limit Order Market. *Journal of Financial Markets*, 2(2):99–134.

Foucault, T., Moinas, S., and Theissen, E. (2007). Does Anonymity Matter in Electronic Limit Order Markets? *The Review of Financial Studies*, 20(5):1707–1747.

Foucault, T., Pagano, M., and Röell, A. (2013). *Market Liquidity: Theory, Evidence and Policy*. Oxford University Press.

Foucault, T., Röell, A., and Sandås, P. (2003). Market Making with Costly Monitoring: An Analysis of the SOES Controversy. *The Review of Financial Studies*, 16(2):345–384.

George, T. J. and Longstaff, F. A. (1993). Bid-Ask Spreads and Trading Activity in the S&P 100 Index Options Market. *Journal of Financial and Quantitative Analysis*, 28(3):381–397.

Gertler, M. and Karadi, P. (2015). Monetary Policy Surprises, Credit Costs, and Economic Activity. *American Economic Journal: Macroeconomics*, 7(1):44–76.

Glosten, L. R. (1994). Is the Electronic Order Book Inevitable? *Journal of Finance*, 49(4):1127–1161.

Glosten, L. R. and Milgrom, P. R. (1985). Bid, Ask and Transaction Prices in a Specialist Market with Heterogeneously Informed Traders. *Journal of Financial Economics*, 14(1):71–100.

Golosov, M. and Tsyvinski, A. (2007). Optimal Taxation with Endogenous Insurance Markets. *Quarterly Journal of Economics*, 122(2):487–534.

Gomez, T. and Piccillo, G. (2023). Does US Monetary Policy Respond to Macroeconomic Uncertainty? CESifo Working Paper No. 10407, CESifo.

Gorton, G. and Ordoñez, G. (2014). Collateral Crises. *American Economic Review*, 104(2):343–378.

Gould, M. D., Porter, M. A., Williams, S., McDonald, M., Fenn, D. J., and Howison, S. D. (2013). Limit Order Books. *Quantitative Finance*, 13(11):1709–1742.

Goyal, A. and Saretto, A. (2009). Cross-Section of Option Returns and Volatility. *Journal of Financial Economics*, 94(2):310–326.

Green, T. C. and Figlewski, S. (1999). Market Risk and Model Risk for a Financial Institution writing Options. *The Journal of Finance*, 54(4):1465–1499.

Haddad, V., Moreira, A., and Muir, T. (2021). When Selling Becomes Viral: Disruptions in Debt Markets in the COVID-19 Crisis and the Fed's Response. *The Review of Financial Studies*, 34(11):5309–5351.

Hattori, M., Schrimpf, A., and Sushko, V. (2016). The Response of Tail Risk Perceptions to Unconventional Monetary Policy. *American Economic Journal: Macroeconomics*, 8(2):111–36.

Hertrig, M. and Zimmermann, H. (2017). On the Credibility of the Euro/Swiss Franc Floor: a Financial Market Perspective. *Journal of Money Credit and Banking*, 49(2–3):567–578.

Ho, T. and Stoll, H. R. (1981). Optimal Dealer Pricing under Transactions and Return Uncertainty. *Journal of Financial Economics*, 9(1):47–73.

Hollifield, B., Miller, R. A., and Sandås, P. (2004). Empirical Analysis of Limit Order Markets. *The Review of Economic Studies*, 71(4):1027–1063.

Holló, D., Kremer, M., and Lo Duca, M. (2012). CISS – A Composite Indicator of Systemic Stress in the Financial System. Technical report, European Central Bank, Working Paper Series, No. 1426.

Jameson, M. and Wilhelm, W. (1992). Market Making in the Options Markets and the Costs of Discrete Hedge Rebalancing. *The Journal of Finance*, 47(2):765–779.

Jarociński, M. (2022). Central Bank Information Effects and Transatlantic Spillovers. *Journal of International Economics*, 139(103683).

Johnson, T., Liang, M., and Liu, Y. (2016). What Drives Index Options Exposures? *Review of Finance*, 22(2):561–593.

Kaeck, A., van Kervel, V., and Seeger, N. J. (2021). Price Impact versus Bid–Ask Spreads in the Index Option Market. *Journal of Financial Markets*, page 100675.

Kandel, S., Sarig, O., and Wohl, A. (1999). The Demand for Stocks: An Analysis of IPO Auctions. *The Review of Financial Studies*, 12(2):227–247.

Kargar, M., Lester, B., Lindsay, D., Liu, S., Weill, P.-O., and Zúñiga, D. (2021). Corporate Bond Liquidity During the COVID-19 Crisis. *The Review of Financial Studies*, 34(11):5352–5401.

Kaul, A., Mehrotra, V., and Morck, R. (2000). Demand Curves for Stocks do Slope Down: New Evidence from an Index Weights Adjustment. *The Journal of Finance*, 55(2):893–912.

Krueger, D. and Perri, F. (2006). Does Income Inequality Lead to Consumption Inequality? Evidence and Theory. *Review of Economic Studies*, 73(1):163–193.

Kuttner, K. N. (2001). Monetary Policy Surprises and Interest Rates: Evidence from the Fed Funds Futures Market. *Journal of Monetary Economics*, 47(3):523–544.

Lagos, R. and Zhang, S. (2020). Turnover Liquidity and the Transmission of Monetary Policy. *American Economic Review*, 110(6):1635–1672.

Leland, H. E. (1985). Option Pricing and Replication with Transaction Costs. *Journal of Finance*, 40(5):1283–1301.

Lin, J.-C., Sanger, G. C., and Booth, G. G. (1995). Trade Size and Components of the Bid-Ask Spread. *The Review of Financial Studies*, 8(4):1153–1183.

Lucca, D. O. and Moench, E. (2015). The Pre-FOMC Announcement Drift. *The Journal of Finance*, 70(1):329–371.

Medvedev, A. and Scaillet, O. (2007). Approximation and Calibration of Short-Term Implied Volatilities under Jump-Diffusion Stochastic Volatility. *The Review of Financial Studies*, 20(2):427–459.

Miller, M., Weller, P., and Zhang, L. (2002). Moral Hazard and the US Stock Market: Analysing the 'Greenspan Put'. *Economic Journal*, 112:C171–C186.

Miller, M. and Zhang, L. (2014). *Saving the Euro: Self-fulfilling Crisis and the "Draghi Put"*, pages 227–241. Palgrave Macmillan UK, London.

Miranda-Agrippino, S. and Rey, H. (2020). U.S. Monetary Policy and the Global Financial Cycle. *Review of Economic Studies*, 87:2754–2776.

Mumtaz, H. and Theodoridis, K. (2020). Dynamic Effects of Monetary Policy Shocks on Macroeconomic Volatility. *Journal of Monetary Economics*, 114:262–282.

Muravyev, D. (2016). Order Flow and Expected Option Returns. *The Journal of Finance*, 71(2):673–708.

Muravyev, D. and Pearson, N. D. (2020). Options Trading Costs are Lower than you Think. *The Review of Financial Studies*, 33(11):4973–5014.

O'Hara, M. and Zhou, X. A. (2021). Anatomy of a Liquidity Crisis: Corporate Bonds in the COVID-19 Crisis. *Journal of Financial Economics*, 142(1):46–68.

Palazzo, B. and Yamarthy, R. (2022). Credit Risk and the Transmission of Interest Rate Shocks. *Journal of Monetary Economics*, 130:120–136.

Pan, J. and Poteshman, A. M. (2006). The Information in Option Volume for Future Stock Prices. *The Review of Financial Studies*, 19(3):871–908.

Qontigo (2022). EURO STOXX 50 INDEX, Factsheet. https://www.stoxx.com/factsheets. [Online; accessed March-04-2022].

Romer, C. and Romer, D. (2023). Presidential Address: Does Monetary Policy Matter? The Narrative Approach after 35 Years. *American Economic Review*, 113(6):1395–1423.

Rösch, C. G. and Kaserer, C. (2014). Reprint of: Market Liquidity in the Financial Crisis: The Role of Liquidity Commonality and Flight-to-Quality. *Journal of Banking & Finance*, 45:152–170.

Sandås, P. (2001). Adverse selection and competitive market making: Empirical evidence from a limit order market. *The Review of Financial Studies*, 14(3):705–734.

Schnaubelt, M., Rende, J., and Krauss, C. (2019). Testing Stylized Facts of Bitcoin Limit Order Books. *Journal of Risk and Financial Management*, 12(1):25.

Stoll, H. R. (1978). The Supply of Dealer Services in Securities Markets. *The Journal of Finance*, 33(4):1133–1151.

Tange, O. (2011). GNU parallel – The Command-Line Power Tool. *;login: The USENIX Magazine*, 36(1):42–47.

Vijh, A. (1990). Liquidity of the CBOE Equity Options. *The Journal of Finance*, 45(4):1157–1179.

Wei, J. and Zheng, J. (2010). Trading Activity and Bid-Ask Spreads of Individual Equity Options. *Journal of Banking & Finance*, 34:2897–2916.

Wurgler, J. and Zhuravskaya, E. (2002). Does Arbitrage Flatten Demand Curves for Stocks? *The Journal of Business*, 75(4):583–608.

Part I

Appendix

A Data

A.1 Data sources

We use the following data sources: (*i*) the T7 Enhanced Market Data Interface (EMDI) and T7 Reference Data Interface (RDI) of Deutsche Börse AG, which provide dynamic tick-by-tick order book data and trade data (market data) and, respectively, the static reference data of all products and instruments[29] listed on and executed via the futures exchange Eurex (except for any foreign exchange products); [30] (*ii*) high-frequency calculations (every 15 seconds) of the EURO STOXX 50 price index, which is the underlying asset of the options under consideration, obtained from Deutsche Börse AG; (*iii*) daily open interest data, trading volumes, and put-call ratio statistics on EURO STOXX 50 index options (OESX) procured from Eurex.[31]

A.2 Construction of order book snapshots and data cleaning

We focus on the following option products traded on Eurex: EURO STOXX 50 index options (OESX); EURO STOXX 50, 1st Friday weekly options (OES1); EURO STOXX 50, 2nd Friday weekly options (OES2); EURO STOXX 50, 4th Friday weekly options (OES4).

[29]Note that, with regards to options, Eurex employs the term *instrument* to refer to a particular option, e.g., a put with a given expiry date and strike price, while the term *product* is typically used for all instruments on the same underlying asset. Thus, for each unique product, there are usually a large number of instruments.

[30]Detailed documentation about the EMDI and RDI data can be found in the system documentation of the T7 trading architecture (Deutsche Börse Group, 2019, 2020). Both the reference data and market data are published in the Financial Information eXchange (FIX) message format; see www.fixtrading.org for further information on this protocol.

[31]See `https://www.eurex.com/ex-en/data/statistics/trading-statistics`.

A.2.1 Raw data processing

For each trading day and product of interest, we construct the samples of order book snapshots and associated trades in the following three steps. First, we process the reference data file. From that, we extract the product snapshot message, which provides the static information about the product, such as its currency, the tick size, the unique product ID, etc. The product ID provided by this message is used to extract the reference data messages of all available instruments of the option product (instrument snapshot messages). The instrument snapshot messages in turn provide static information about the instruments, such as the put/call flag, the strike, a unique instrument ID, etc.

Based on these static data, we select the following instruments from the instrument snapshot messages, using the following filters: the instrument status is active, meaning that the instrument is listed and tradable; the exercise style is European; the settlement method is cash; the instrument is a plain vanilla call or put option, i.e., a one-legged instrument (simple instrument in Eurex terminology); the instrument has an expiry date corresponding to a tenor between one and 365 calendar days. We do not apply a filter on strikes. On an average day, this results in 1,672 unique instruments for the OESX product and 275 unique instruments for the OES1, OES2, and OES4 products.

In the second step, we extract the market data messages from the market data file for each instrument. Using the state change messages, we check whether any of the requested instruments enters a problematic state during the continuous phase of the trading day, such as a trading halt. We do not find any problematic states for all requested instruments. There are two types of market data messages for rebuilding the order book: depth snapshot messages and depth incremental messages. Depth snapshot messages are sent by the EMDI on average every eight seconds throughout the trading day and provide a snapshot of the order book and trade data of each instrument. Depth incremental messages provide updates to the order book as well as data on every single trade for each instrument at a nanosecond precision (measured in UTC time). The incremental messages are event dependent, i.e., they are only sent when a change to the order book or a trade occurs.[32] For each instrument of interest, we use the unique instrument ID provided by the instrument snapshot message (contained in the reference data messages) to extract the depth snapshot messages and depth incremental messages of the instrument.[33]

Third, the order book reconstruction works as follows. The depth incremental messages conveying order book updates come with a sequence number and a nanosecond timestamp, which are both increasing with every new depth incremental message. The depth snapshot messages providing order book snapshots contain the last processed sequence number that indicates, which depth incremental messages are already reflected in the given depth snapshot message. Starting from the first depth snapshot message of the continuous phase, we sequentially apply all depth incremental messages, whose sequence number is larger than the last processed sequence number. This procedure allows us to reconstruct the exact state of the order book at any time of interest. In this way, we create order book snapshots every five seconds for every instrument during the continuous phase of each trading day from 9:05 to 17:25 hrs CET. We exclude the first and last five minutes of the continuous trading phase in order to avoid dealing with different lengths of the continuous phase. The starting times of the continuous phase differ because the opening auctions have different durations but always end within the first five minutes of the trading day.

A.2.2 Data structure, key variables, and filter criteria

The EMDI data provide the five best price levels on the bid and ask side of the order book of the products of interest. Depending on the liquidity, fewer price levels may be available. Also one-sided order books are admissable. At each price level of the created order book snapshot, we observe the price and the consolidated quantity of the contracts demanded or supplied at that price. Importantly, we do not observe the quantity of

[32]The EMDI employs the following types of order book updates: insertion of a new price level; change of any variable (except the price), such as the quantity, on a given price level; change of the price and any other variables on a given price level; deletion of a price level; deletion of all price levels that are equal to or deeper than a given price level; deletion of all price levels that are equal to or less deep than a given price level (Deutsche Börse Group, 2020, pp. 54–59).

[33]We make use of GNU parallel developed by Tange (2011).

single orders in the order book, however, we do observe the number of orders at each price level. We also know the timestamp of the order book snapshot.

Concerning data on trades for both market and limit orders, we observe, among other variables, the price, quantity, aggressor side (bid or ask), execution timestamp in nanoseconds (UTC), and whether the trade is on-book or off-book (OTC). If an order executes against multiple price levels, then multiple trades are reported, one for each price level that the order executes against.

We perform the following sanity checks on the order book snapshots where none of the checks led to data losses: keep only snapshots where all bid and ask prices are positive; keep only snapshots where all bid and ask quantities are positive; eliminate snapshots with missing prices, quantities, number of orders, bid and ask side indicators, timestamps or price level indicators; require the spread to be equal to or larger than the minimum tick size (0.10 index points corresponding to €1); check if the first difference between prices is equal to or larger than the minimum tick size implying a strictly monotone price schedule. As regards trade data, we remove all trades that were reversed, canceled due to self-match prevention, manually entered by the Eurex market supervision, or have a non-missing trade type indicator because they are related to auctions. We also delete trades that are executed as part of a complex instrument (multi-leg option strategy) since they do not affect the order book of the simple instruments. After applying these filters, we verify that the trade size and the trade price are both positive. See Goyal and Saretto (2009), Cenesizoglu and Grass (2018), and Andersen et al. (2021) for applications of similar filters.

Furthermore, the EMDI data allow us to continuously verify the consistency of the order book when rebuilding it. For example, when a depth incremental message indicates a quantity change on the first price level of the bid side, we can use the price included in the message to check whether it matches with the best bid price of the current state of the order book. Moreover, the parser provided by the Deutsche Börse AG enables gap checking of messages containing a sequence number, such as the depth incremental messages. We did not find any errors. Finally, we note that for 99.92% of all instruments, we observe either a depth snapshot file containing non-empty order book snapshots and a non-empty depth incremental file, or a depth snapshot file consisting only of empty order book snapshots and an empty depth incremental file. All the checks confirm that the data are complete and of very high quality. We therefore do not apply any filters that eliminate books with very large spreads as is done in some empirical work. We consider them genuine and not a result of measurement error. Table 4 shows summary statistics for the filtered data set.

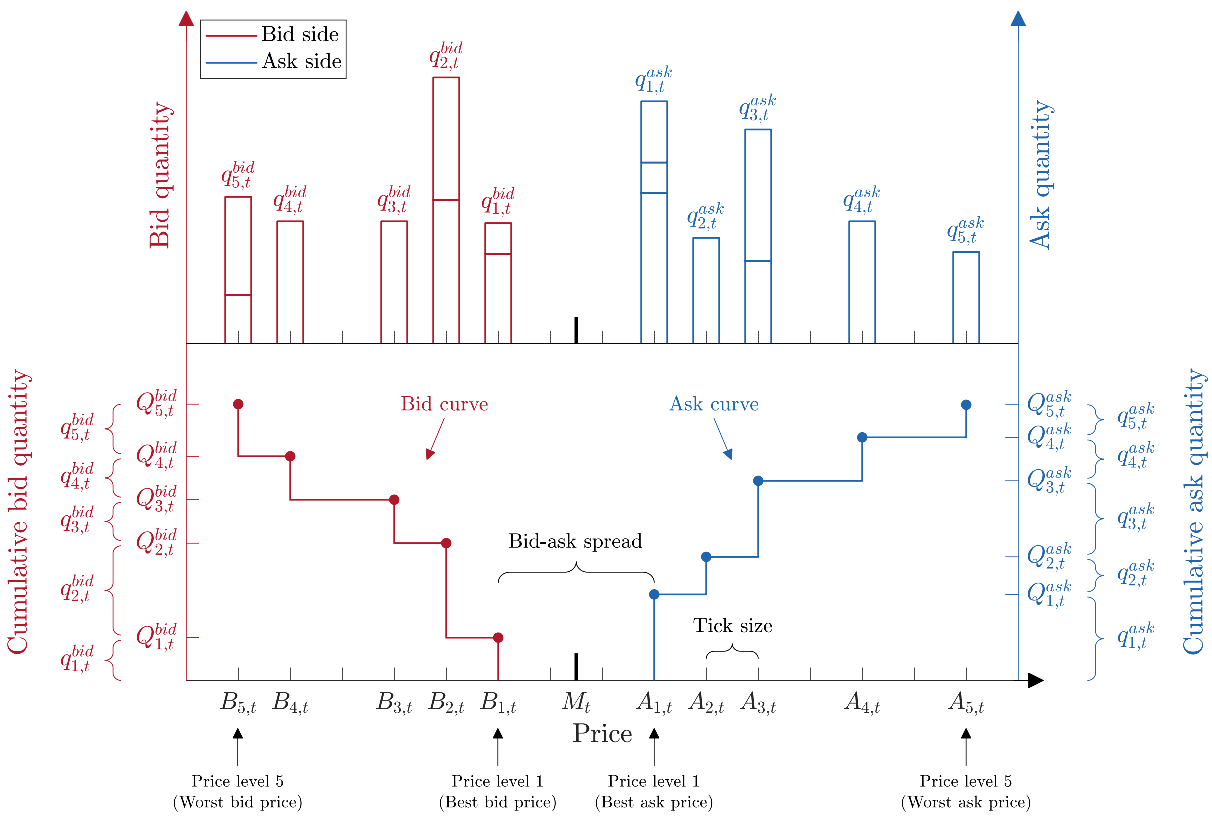
Table 4: Summary statistics.

Variable	Mean	Std. Dev.	5%	50%	95%
On-book trade statistics					
Daily number of trades	5,181	3,683	1,921	4,110	13,251
Daily trading volume (€million)	158.62	163.22	33.83	100.67	552.11
Daily trading volume (contracts, 1000s)	237.07	153.45	93.77	191.96	575.42
Trade size (contracts)	46	97	1	10	200
Aggressor side (bid = 0, ask = 1)	0.49	0.50	0	0	1
Put/call (put = 0, call = 1)	0.43	0.49	0	0	1
Trade price (in index points = 10€)	84.43	129.74	1.90	44.70	285.00
Tenor (days)	71	74	14	38	259
Standardized moneyness	−0.38	1.39	−3.21	−0.07	1.30
Log-forward moneyness	−0.03	0.17	−0.31	−0.01	0.18
Implied volatility	0.31	0.17	0.11	0.27	0.68
EURO STOXX 50 index level	3,175.76	429.87	2,408.07	3,208.52	3,805.2
Off-book trade statistics					
Daily number of trades	33	22	10	27	81
Daily trading volume (€million)	166.47	268.03	13.50	78.15	688.43
Daily trading volume (contracts, 1000s)	151.05	113.81	32.27	124.20	393.73
Trade size (contracts)	4,586	4,220	1,103	3,000	14,000
On-book liquidity statistics					
Bid elasticity	−81.1	72.1	−216.5	−64.8	−2.6
Ask elasticity	79.0	73.9	2.1	62.1	215.9
Relative spread	0.042	0.062	0.008	0.022	0.144
Number of order book updates per minute	470	584	0	224	1,678

Notes: Statistics are based on simple instruments within the standardized moneyness range $[-6, 3]$ and tenor range $[10, 365]$. Complex instrument trades are excluded.

B Liquidity measurement

Figure 4 illustrates a typical snapshot of the order book. In the following, we explain the statistics we use to characterize liquidity: the average market depth measured in terms of bid and ask elasticities and average relative spreads.



Sources: Own illustration based on illustrations in Gould et al. (2013), Foucault et al. (2013, p. 195), Schnaubelt et al. (2019). *Notes:* The upper plot shows the non-cumulative order book. The stacked bars refer to multiple orders. E.g., $q^{bid}_{5,t}$ consists of two orders and $q^{bid}_{4,t}$ of one order. Note, however, that we do not observe the size of the single orders as could be implied by the illustration. The lower plot shows the cumulative order book, i.e., the bid and ask curve.

Figure 4: Illustration of an order book snapshot at time t.

B.1 Calculation of average bid and ask schedules

The estimates of the price elasticity based on the bid and ask schedules of the five-seconds snaphots are highly sensitive to the random fluctuations affecting the order book. For option order books, this is particularly relevant because liquidity may suddenly arrive or dry up as the option moves in or out of certain moneyness ranges during the trading day. For this reason, we compute average bid and ask schedules by price level averaging over time, as first suggested in Biais et al. (1995), to render the elasticity estimates more robust. To this end, we structure the five-seconds snapshots between 9:05 and 17:25 hrs CET of the continuous phase of each trading day into five-minutes intervals.

To compute the average bid and ask schedules for each five-minute interval, we start by denoting the bid and ask quantity at price level ℓ at some time t as $q^{bid}_{\ell,t}$ and $q^{ask}_{\ell,t}$. The *cumulative* quantity for bids and asks, respectively, for instrument j up to price level L at time t is then given by

$$Q^{k}_{j,L,t} = \sum_{\ell=1}^{L} q^{k}_{j,\ell,t} \ , \quad k = \{ask, bid\} \ . \tag{B.1}$$

Replacing the generic time t by the triple (d, i, s), we define the *average* cumulative bid and ask quantity for instrument j at price level L on trading day d in time interval i by averaging across snapshots s within time interval i so that

$$\bar{Q}^{k}_{j,L,d,i} = \frac{1}{S_{j,d,i}} \sum_{s=1}^{S_{j,d,i}} Q^{k}_{j,L,d,i,s} \ , \quad k = \{ask, bid\} \ , \tag{B.2}$$

where $S_{j,d,i}$ denotes the total number of snapshots of instrument j on day d in time interval i. Turning from quantities to prices, we define the average bid and ask price of instrument j at price level L on trading day d in time interval i as

$$\bar{B}_{j,L,d,i} = \frac{1}{S_{j,d,i}} \sum_{s=1}^{S_{j,d,i}} B_{j,L,d,i,s} \ , \qquad \bar{A}_{j,L,d,i} = \frac{1}{S_{j,d,i}} \sum_{s=1}^{S_{j,d,i}} A_{j,L,d,i,s} \ , \tag{B.3}$$

where $B_{j,L,d,i,s}$ is, for example, the bid price of instrument j at price level L on trading day d in time interval i's snapshot s.

The average bid and ask schedules are given by (B.2) and (B.3). As mentioned above, we set the interval length to five minutes so that each time interval consists of up to 60 snapshots. The average bid or ask schedule may be based on fewer than 60 snapshots because we consider a bid or ask side snapshot only if the order book is deep enough, in the sense that it contains five price levels (maximum number of visible price levels in our data). Hence, our average bid and ask schedules have five price levels each. To mitigate the influence of potential outliers and microstructure artifacts, we require at least 20 snapshots on the bid or ask side per time interval.[34] If at least 20 bid (ask) side snapshots and less than 20 ask (bid) side snapshots exist in a time interval, we compute the average bid (ask) schedule but no average ask (bid) schedule.

B.2 Market depth

The constructed average bid and ask schedules on quantities and prices allow us to estimate market depth as the price elasticity of the ask and bid side. The larger the elasticity, the smaller are the price changes if market participants want to trade larger quantities. A larger elasticity (in absolute terms) of quantities with respect to price changes thus implies deeper and more liquid markets.

We compute the bid elasticity $\zeta^{bid}_{j,d,i}$ of instrument j on trading day d in time interval i based on the log-log regression:

$$\log(\bar{Q}^{bid}_{j,L,d,i}) = \alpha_{j,d,i} + \zeta^{bid}_{j,d,i} \log(\bar{B}_{j,L,d,i}) + \varepsilon_{j,L,d,i} \, , \tag{B.4}$$

where the sample ranges over $L = 1, \ldots, 5$. The ask elasticity is computed analogously. For each five-minute interval, we thus obtain the bid and ask elasticities of all available instruments.

The elasticity may depend on the moneyness and the tenor of the options. We therefore sort the estimates into moneyness/tenor buckets $m \times \tau$ and $\mu \times \tau$ where

log-forward moneyness: $m = \{-0.3, -0.1, -0.05, 0, 0.05, 0.1, 0.3\}$,
standardized moneyness: $\mu = \{-6, -3, -2, -1, 0, 1, 2, 3\}$,
tenor (in calendar days;) $\tau = \{10, 46, 81, 121, 365\}$.

This yields 24 buckets for $m \times \tau$ and 28 buckets for $\mu \times \tau$. See Appendix E.1 and E.2 for

[34] For the computation of the elasticity and the spread in the intraday analysis, we require only one snapshot for the calculation of the average bid and ask schedules. For the relative spreads at an intraday frequency, we require the average bid and ask schedules to contain at least one price level.

the definitions of moneyness mentioned above.

We estimate the unconditional bid elasticity by averaging the bid elasticity estimates in bucket b, i.e.,

$$\bar{\xi}_b^{bid} = \frac{1}{N_b} \sum_{d=1}^{D} \sum_{j=1}^{J} \sum_{i=1}^{I} \xi_{j,t}^{bid} \mathbb{1}_{\{j \in b, t=(d,i)\}} \ , \tag{B.5}$$

where N_b denotes the total number of bid elasticity estimates that fall into b and $\mathbb{1}_A$ denotes the indicator function of the event A. For the daily time series of bid elasticities, we compute the average bid elasticity of bucket b on day d as

$$\bar{\xi}_{b,d}^{bid} = \frac{1}{N_{b,d}} \sum_{j=1}^{J} \sum_{i=1}^{I} \xi_{j,t}^{bid} \mathbb{1}_{\{j \in b, t=(d,i)\}} \ , \tag{B.6}$$

where $N_{b,d}$ denotes the number of bid elasticity estimates that fall into the bucket b on day d. Clearly, for the intraday analysis, we do not average over the intraday time intervals i. All estimates of the ask side are defined analogously.

B.3 The relative spread

As for the elasticity, we compute the relative spread based on the average bid and ask schedules.[35]. The mid price of instrument j on trading day d in time interval i is defined as

$$\bar{M}_{j,d,i} = \frac{\bar{A}_{j,1,d,i} + \bar{B}_{j,1,d,i}}{2} \tag{B.7}$$

so that the relative spread of instrument j on trading day d in time interval i is

$$RS_{j,d,i} = \frac{\bar{A}_{j,1,d,i} - \bar{B}_{j,1,d,i}}{\bar{M}_{j,d,i}} \tag{B.8}$$

[35]Here, the average bid and ask prices are based only on snapshots that consist of both a bid and ask side.

B.4 Market depth and hedging costs

Given an estimated elasticity ξ as defined in Appendix B.2, the factor capturing the price effect of trading quantity Q is captured by $Q^{\frac{1}{\xi}}$. For a fully elastic supply on the bid side (or fully elastic demand on the ask side), i.e., for deep and liquid markets, $|\xi| \to \infty$ so that there is no price change implied by trading larger quantities (the factor $Q^{\frac{1}{\xi}} = 1$). The price change attains infinity instead if the respective other side of the market is fully illiquid so that $\xi \to 0$. For intermediate ξ, the marginal price change depends on the traded quantity Q.

We compute $\Delta M(Q)$, the change in the price of trading quantity Q which results from changes in market depth, as the average of the price changes up to that traded quantity, i.e.,

$$\Delta M(Q) = \frac{1}{Q}\left[\int_0^Q x^{\frac{1}{\xi_{\text{pre}}}}\,\mathrm{d}x - \int_0^Q x^{\frac{1}{\xi_{\text{post}}}}\,\mathrm{d}x\right] \tag{B.9}$$

$$= \frac{\xi_{\text{pre}}}{\xi_{\text{pre}}+1} Q^{\frac{1}{\xi_{\text{pre}}}} - \frac{\xi_{\text{post}}}{\xi_{\text{post}}+1} Q^{\frac{1}{\xi_{\text{post}}}}, \tag{B.10}$$

where we apply the uniform weight $1/Q$ when taking the average; ξ_{pre} denotes the elasticity in the pre-event window and ξ_{post} the elasticity in the post-event window.

If we set Q to the number of contracts required to hedge a portfolio worth 1 MM, we obtain the price effect of the event resulting from changes in market depth, which is then added to the effects of the event on the option price and the spread.

Part II

Supplementary appendix

C Implied volatility and forward prices

Precise calculation of IV is of paramount importance to our analysis because the attribution of the observations to the moneyness buckets we create depends on it. Although it is conceptually straightforward to find the level of volatility that equates the Black-Scholes option pricing function with observed market prices of options, it is a challenge to do so with interest rate data and *expected* dividend information about the underlying asset that is consistent with the option data at the time of observation. This is difficult to ensure with historical data because interest rate data procured from external sources may not fully reflect the counterparty risk that market participants associate with the derivatives positions they clear via Eurex. Moreover, forward-looking dividend information is hardly available. For this reason, it is more accurate to work with risk-free rates and dividend yields implied from observed option data by means of the put-call parity. Similar considerations apply to the computation of forward prices. In this section, we explain the procedure in detail, which is close to the one described in Audrino and Fengler (2015).

C.1 Implied dividend yield and implied risk-free rate

Key to the procedure is to exploit the put-call parity, $M^{call} - M^{put} = e^{-q\tau}S - e^{-r\tau}K$, where we denote by M the mid price of a call and a put with strike price K and a fixed unique tenor τ, assuming continuous dividend yields q and continuously compounded interest rates r. Both depend on τ, but we suppress this additional notation. Lastly, S denotes the concurrent price level of the EURO STOXX 50 index. While no-arbitrage theory requires this equation to hold at any point in time, market microstructure frictions, such as the bid-ask spread, may lead to tiny violations. We therefore cast the put-call parity into the regression model

$$M^{call} - M^{put} = \alpha + \beta K + \epsilon\,, \tag{C.1}$$

where $\alpha = \mathrm{e}^{-q\tau}S$ and $\beta = -\mathrm{e}^{-r\tau}$ by the put-call parity.

To estimate (C.1), we extract, on each day, the order book snapshots of all instruments, puts and calls, within a log-forward moneyness range from 0.9 to 1.1. We use all available tenors (between 1 and 365 days) and make sure that the snapshot times coincide with the 15 second calculations of the EURO STOXX 50 index at our disposal. It is important to stress that we estimate (C.1) as a cross-sectional regression per snapshot time. We thus obtain, for each order book snapshot time s on each day d and for each available tenor τ, the estimates $\hat{\alpha}^{\tau}_{d,s}$ and $\hat{\beta}^{\tau}_{d,s}$. These coefficient estimates allow us to back out the implied dividend yield and risk-free interest rate as

$$\hat{q}^{\tau}_{d,s} = \frac{-\log(\hat{\alpha}^{\tau}_{d,s}/S_{d,s})}{\tau} \tag{C.2}$$

and

$$\hat{r}^{\tau}_{d,s} = \frac{-\log(-\hat{\beta}^{\tau}_{d,s})}{\tau}\,. \tag{C.3}$$

The estimates are high-frequent, one for each 15 second snapshot; however, we aggregate them to daily estimates in order to obtain robust estimates. To this end, we compute the median of all available within-day estimates, i.e., $\hat{q}^{\tau}_{d} = \mathrm{Med}\{\hat{q}^{\tau}_{d,s}\}$, $\hat{r}^{\tau}_{d} = \mathrm{Med}\{\hat{r}^{\tau}_{d,s}\}$, and $\hat{\gamma}^{\tau}_{d} = \mathrm{Med}\{\mathrm{e}^{(\hat{r}^{\tau}_{d,s}-\hat{q}^{\tau}_{d,s})\tau}\}$, which denotes the adjustment factor necessary to derive the forward price. Depending on data availability, the median is based on up to 2001 regression estimates per day. For those few days, for which an estimate is not feasible for a certain tenor due to lack of data, we obtain it by a linear interpolation across the tenors on that given day.

The high-frequency estimate of the implied forward for tenor τ is given by

$$F^{\tau}_{d,s} = \hat{\gamma}^{\tau}_{d} S_{d,s}\,, \tag{C.4}$$

valid at any 15-seconds snapshot time. We also utilize the pair $(\hat{q}^{\tau}_{d}, \hat{r}^{\tau}_{d})$ to calculate high-frequency estimates of IV, by way of equating the observed market prices of options with the Black-Scholes option pricing function.

D The informational content of options with short tenor

D.1 Illustrations

Standard option pricing theory assumes that the underlying price process follows an Itô semimartingale on a filtered probability space and the absence of arbitrage opportunities in financial markets. By the fundamental theorem of asset pricing, option prices are functions of a set of parameters and a vector of variables that govern the state of the underlying price process and its future evolution under a risk-neutral measure. Option traders learn about the state variables by observing option quotes and trades. Whereas a single option price does not allow them to disentangle information about the different state variables, a cross-section of options with different tenors and strikes issued on the same underlying asset does.

Option pricing theory has substantiated this dependence. Medvedev and Scaillet (2007) and Durrleman (2008) prove that the IV of an option with strike equal to the underlying price converges to the spot volatility as the tenor converges to zero.[36] Thus, order books and prices of short-dated ATM options provide significant information about the state of spot volatility. Additionally, research by Bollerslev and Todorov (2011, 2014) and Andersen et al. (2015, 2020) has shown that far OTM puts and calls with short tenors can reveal information about downside and upside jump risks.

To illustrate these insights, we employ an option pricing model close to Andersen et al. (2017, App. H)—see Appendix D.2 for a concise description including its parametrization. Our model has two variance factors, leverage, and jumps in the price and the variance process. The jumps in the price process follow an asymmetric exponential distribution, where the variance increases whenever there is a negative jump in the price process, creating a threshold-GARCH-like effect. We emphasize that the exact

[36] These results hold for an Itô semimartingale with finite variation jumps.

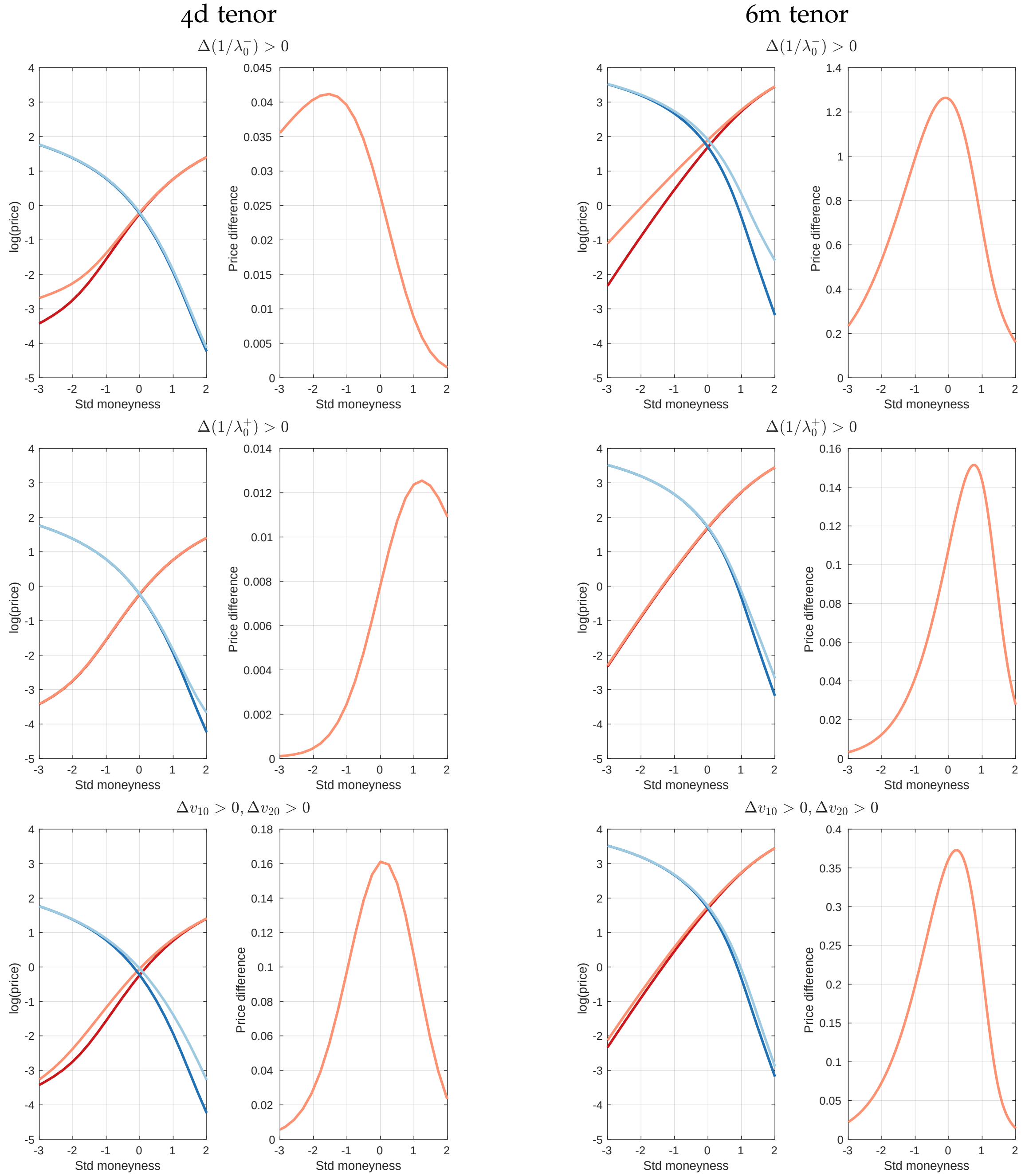
specification of the model is not essential for our purposes because the cited properties hold for all option pricing models that build on an Itô semimartingale for the underlying asset.

Figure 5 illustrates the effect on both call and put prices resulting from a change in a specific parameter or state variable of interest. We contrast options with short tenor in the left panel (four days) with options with a longer tenor (six months) in the right panel. Within each panel, the left plots show the log prices of calls (blue) and puts (red); lighter colors correspond to the log prices after the shift. The right plots show the absolute price difference resulting from the parameter shift (not the logarithmic price difference).

The top row of Figure 5 illustrates how an increase of the expected downward jump size, given by $1/\lambda_0^-$, affects option prices as a function of standardized moneyness. The plot of the log price function (first figure from the left) exhibits that only the left tail of the short-tenor log put price function reacts in a significant manner, whereas the log prices of ITM puts, ITM calls, and OTM calls appear to barely respond. The second figure from the left sheds light on the resulting absolute price differences, which are are largest in the standardized moneyness region of about -2 as the cited theory predicts.

Comparing these findings with those for six-months options in the right panel in the top row of Figure 5, we observe a qualitatively similar reaction for OTM puts. OTM calls with a longer tenor, however, get more expensive, too. In our illustrative model, this happens because the size of downward jumps is positively linked to the size of the upward jumps in the variance. However, the increase in the expected downward jump size now affects both put and call prices. This makes it more difficult to separate the effect of changes in the expected downward jump size on option prices from changes of other factors which impact option prices.

The middle row of Figure 5 illustrates the effect of an increase in the expected upward jump size $1/\lambda_0^+$. In this case, prices of the OTM calls respond most, both for short and long tenors. Prices of the six-months OTM puts do not react strongly because in our illustrative model the upward jumps are independent from variance jumps. Overall, the effects are less pronounced than for the downward jumps in the top row because, in line with empirical evidence, the parametrization implies that upward jumps have a lower



Sources: Own calculations. *Notes:* The plot illustrates certain characteristics of an option price with a tenor of four days (left panel) and six months (right right panel). Within each panel, the left plot shows the log price of a call (blue) and a put (red). Lighter colors indicate the price function after shifting the parameter or state variable mentioned in the title, where $1/\lambda_0^-$ is the expected downside jump size, $1/\lambda_0^+$ the expected upside jump size, and $v_0 = v_{1,0} + v_{2,0}$ is the total initial variance factor. The right plots show the difference of the option price after the shift minus the option price before the shift (light red color). For European style options, $\Delta C_0 = \Delta P_0$ by the put-call parity. All parameters and state variables are shifted by 50%. The underlying pricing model features two stochastic volatility factors, leverage, and jumps in the price and the volatility process; see Appendix D.2 for the details.

Figure 5: Option price responses to increases in the jump size or the initial variance

jump intensity. This dampens the responsiveness of option prices. The main message again is that the reaction of short-dated call options allows to identify the shock to the expected upward jump size.

In the bottom row of Figure 5, we show the corresponding pictures resulting from changes in the state of total initial variance $V_0 = V_{1,0} + V_{2,0}$. The patterns differ significantly from those reported for the jump sizes in that option prices with short tenor, both ATM calls *and* puts, exhibit the largest changes in magnitude.

In Figure 6, we present the responses of option prices to changes in the downside and upside jump intensity of price jumps. The conclusions are similiar.

The experiments highlight that short-dated options provide critical insights into specific state variables. Far OTM puts and calls are particularly sensitive to changes in jump size or intensity, while ATM options respond more to volatility changes. However, as tenor increases, these effects become less distinct. This makes the order books of short-dated options a rich source of information about variance and jump risk characteristics, depending on the option's moneyness.

D.2 Details on the option pricing model

The model we consider is a simplified version of the model discussed in Andersen et al. (2017, App. H) and using their parametrization. The model features two stochastic variance factors implying a total variance state $V_t = V_{1,t} + V_{2,t}$, a leverage effect, and jumps in the price and the variance process.

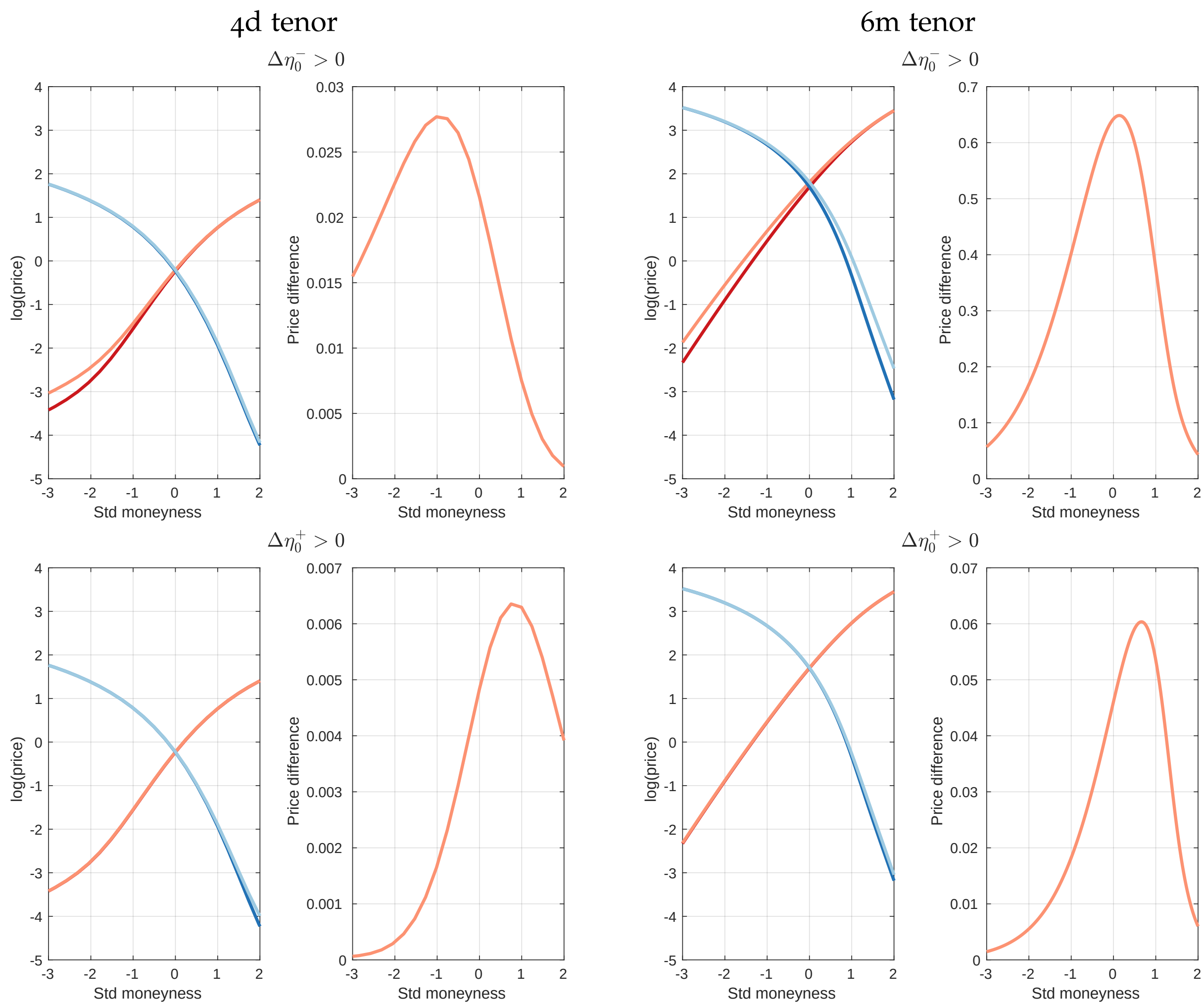
Denote the asset price by S_t. Under the risk-neutral measure, we assume that

$$\frac{\mathrm{d}S_t}{S_{t^-}} = \sqrt{V_t}\,\mathrm{d}W_t + \int_{\mathbb{R}^2} (\mathrm{e}^x - 1)\tilde{\mu}(\mathrm{d}t, \mathrm{d}x, \mathrm{d}y) \tag{D.1}$$

$$\mathrm{d}V_{1,t} = \kappa_1(\theta_1 - V_{1,t})\,\mathrm{d}t + \sigma_1\sqrt{V_{1,t}}\,\mathrm{d}B_{1,t} + \int_{\mathbb{R}^2} y\mu(\mathrm{d}t, \mathrm{d}x, \mathrm{d}y) \tag{D.2}$$

$$\mathrm{d}V_{2,t} = \kappa_2(\theta_2 - V_{2,t})\,\mathrm{d}t + \sigma_2\sqrt{V_{2,t}}\,\mathrm{d}B_{2,t} \tag{D.3}$$

where κ_i, θ_i, $\sigma_i > 0$, $i = 1, 2$, and $(W_t, B_{1,t}, B_{2,t})$ is a three-dimensional Brownian motion. The correlation structure is $\mathrm{Corr}[\mathrm{d}W_t, \mathrm{d}B_{1,t}] = \rho_1\sqrt{V_{1,t}/V_t}$, $\mathrm{Corr}[\mathrm{d}W_t, \mathrm{d}B_{2,t}] = \rho_2\sqrt{V_{2,t}/V_t}$,



Sources: Own calculations. *Notes:* The plot exhibits certain characteristics of an option price with a tenor of five days (left panel) and one year (right right panel). Within each panel, the left plot shows the log price of a call (blue) and a put (red). Lighter colors indicate the price function after shifting the parameter or state variable given in the title, where η_0^- is the downside jump intensity, η_0^+ is the upside jump intensity. The right plots show the difference of the option price after the shift minus the option price before the shift (light red color). For European style options, $\Delta C_0 = \Delta P_0$ by put-call parity. All parameters are shifted by 50%.

Figure 6: Option price responses to increases in the jump intensity parameters η^- and η^+

with $\rho_i \in (-1, 1)$, and $\text{Corr}[\mathrm{d}B_{1,t}, \mathrm{d}B_{2,t}] = 0$. Furthermore, $\mu(\mathrm{d}t, \mathrm{d}x, \mathrm{d}y)$ is an integer-valued measure that counts the jumps in S and V_1 of size $\mathrm{d}x$ and $\mathrm{d}y$, respectively, over $\mathrm{d}t$. The associated jump compensator is $\nu(\mathrm{d}x, \mathrm{d}y)$, and $\tilde{\mu}(\mathrm{d}t, \mathrm{d}x, \mathrm{d}y) = \mu(\mathrm{d}t, \mathrm{d}x, \mathrm{d}y) - \mathrm{d}t\nu(\mathrm{d}x, \mathrm{d}y)$ is the martingale jump measure. The jump specification is

$$\frac{\nu(\mathrm{d}x, \mathrm{d}y)}{\mathrm{d}x\,\mathrm{d}y} = \eta^- \mathbb{1}_{\{x<0, y>0\}} \lambda_- \mathrm{e}^{-\lambda_-|x|} \lambda_v \mathrm{e}^{-\lambda_v y} + \eta^+ \mathbb{1}_{\{x>0, y=0\}} \lambda_+ \mathrm{e}^{-\lambda_+ x}\,. \tag{D.4}$$

Thus, negative price jumps and positive variance jumps occur simultaneously but have independently exponentially distributed jump sizes with parameter $\lambda_i > 0$, $i \in \{+, -, v\}$. The expected jump size is $1/\lambda_i$. This differs from Andersen et al. (2017) in that the variance jumps are not deterministically linked to the price jumps. Moreover, we model the jump intensities $\eta^+ > 0$ and $\eta^- > 0$ as constants, which suffices for our purposes.

The specification is exponentially affine in the state variables. Thus, options can be priced along the lines of Duffie et al. (2000).

Table 5: Parameters of the option pricing model.

Parameter	Value	Parameter	Value	Parameter	Value
κ_1	10.650	κ_2	2.200	η^-	2.110
θ_1	0.004	θ_2	0.017	η^+	1.650
σ_1	0.2901	σ_2	0.272	λ_-	21.555
ρ_1	−0.999	ρ_2	−0.999	λ_+	48.775
				λ_v	14.000

Notes: The parameters are taken from Andersen et al. (2017, Table H.I). The following exceptions apply. The jump intensities η^+ and η^- are set to their expected values, given the numbers reported there, and λ_v is chosen such that our exponentially distributed variance jumps have the same expected jump size as would be implied by their parametrization.

E Supplementary facts about the order books

This section contains supplementary facts that support the analysis in the main text. We summarize the stylized facts of the option order book data and the trends in market liquidity measures over the sample period in Appendix E.1 and E.2. This provides the context to understand the magnitude of the estimated effects in Section 4. Appendix E.3 offers an interpretation of the stylized facts through the lens of market microstructure theory, which provides further background for the interpretation of the monetary policy effects in Section 4.4.

E.1 Stylized facts of the option order books by moneyness and tenor

We summarize the key stylized facts of option order book data as presented in Tables 6 and 7. The summary is valuable in its own right because apparently there does not exist a systematic documentation of stylized facts for option order books and certain statistics we can report have not been documented yet in the literature.[37]

We report the data on the standardized moneyness metric $\log(K/F)/\sigma\sqrt{\tau}$, where F denotes the forward, K the strike, σ the option IV, and τ the tenor. This allows us to create buckets of strike ranges that can be interpreted as multiples of tenor-adjusted at-the-money (ATM) Black-Scholes *sigmas*, notwithstanding the substantial time-variation of IV documented in Figure 1. As Andersen et al. (2021), we observe a tendency towards trading and quoting in negative strike ranges, in which puts are out-of-the-money (OTM) and calls are in-the-money (ITM). This explains the asymmetric layout concerning the moneyness buckets in Tables 6 and 7 and may reflect a downside hedging motive of non-market making market participants.

The values reported for each moneyness-tenor bucket in Table 6 are computed using *all* instruments falling into the respective bucket, and thus are derived from multiple order books of different instruments. More specifically, option prices, {spreads}, ⌜average lot size per trade⌟, and the ⟨update frequency⟩ are the statistics of the order book obtained by *averaging* across all instruments in each bucket and across time. In contrast, the (number of daily trades) and the ⟦daily trading euro volume in millions⟧ are averages of the daily values obtained by *cumulating* across all instruments that fall into the respective bucket.

[37] Among the first to document stylized facts of option data is George and Longstaff (1993), studying S&P 100 options. More recently, Andersen et al. (2021) focus on selected U.S. stock options and options on index-driven US-traded ETFs disseminated by the Options Price Reporting Authority (OPRA). They do not cover stock index options and do not report lot sizes and quantity-price elasticities as we do.

Key stylized facts

1. Across all tenors, {relative spreads} decrease strongly from OTM toward ATM strikes, but only insignificantly from ATM toward ITM strikes. ATM spreads range between 1.6% and 4.2%, which is only half as big as usually reported for options on single stocks included in the S&P500 index.[38]

2. While ITM put versus ITM call {relative spreads} are largely similar, OTM call spreads tend to be much larger than OTM put spreads: e.g., in the moneyness range $[1,2]$, the spreads of OTM calls are more than five times larger than the spreads of OTM puts in the corresponding moneyness range $[-2,-1]$.[39]

3. Trading activity is heterogeneous across the different buckets. Measured by the (cumulative number of daily trades), slightly OTM options are traded most heavily, particularly so short-dated options. ITM options are traded scarcely, while (short-dated) deep OTM puts are still traded in moderate numbers.

4. For puts in the moneyness range $[-1,0]$ and $[0,1]$, the trading activity measured by the cumulative ⟦daily trading volume in MM euro⟧ shows that the long-dated tenors of 121 to 365 days to expiry are economically more important than the heavily traded short-dated tenors. For calls, the trading activity is more balanced, but lower. Indeed, the combined daily trading volume of puts in the buckets of $[-1,0]$ and $[0,1]$ across *all* tenors is twice as large as that of calls in these buckets (about €87 versus €41 MM).

5. Trading activity measured by the ⌈average lot size per trade⌉ is fairly constant across tenors, except for the extreme strike ranges, and similarly sized across near-the-money puts and calls. A salient pattern is that lot sizes increase substantially the more the options are OTM: e.g., the lot size is about twice as large for far OTM puts (57 – 84) than near-the-money puts (33 – 45).

[38]Compare Christoffersen et al. (2018, Table 2) or Muravyev and Pearson (2020, Table 2). The spreads are even smaller than the relative spreads of ATM options on the SPY ETF reported in Andersen et al. (2021, Fig. 11, Tables A.6-A.7) and on ATM SPX options (Kaeck et al., 2021, Table 1).

[39]Andersen et al. (2021) report similar patterns for single stock options and SPY options, but in comparison to the latter, the differences we document are quantitatively smaller.

6. The ⟨number of order book updates per minute⟩,[40] as a measure of order book activity, is highest for near-the-money options, with about 1,000 updates per minute, as well as for short-dated options in general.[41] OTM puts tend to receive many more updates than OTM calls in corresponding buckets, whereas the updates for ITM calls tend to exceed those of both OTM and ITM puts. The latter is surprising, given the low trading activity in ITM calls noted earlier.[42]

7. Table 7 shows that put market depth, measured as a quantity-price elasticity,[43] is largest ATM, decreases for OTM and ITM puts, and vanishes for ITM puts beyond the [1,2] bucket. Call market depth is similar to that of puts, except for ITM calls, where market depth is as large as ATM, despite the low trading volume in these options. Bid and ask sides of both calls and puts are fairly symmetric. The ATM quantity-price elasticities of options imply a market depth that appears to be considerably larger than market depths commonly reported for order books of stocks.[44]

In parts, the stylized facts of EURO STOXX 50 option order books in Tables 6 and 7 echo findings known from empirical work on option markets and market microstructure. For instance, we also find that index puts as downside hedging instruments are economically more relevant than index calls and that the most actively traded options

[40] The statistic on order book updates records any order book revision triggered by either market makers or non-market makers, such as new entries and deletions of price levels, among others. See Footnote 32 for the exhaustive list.

[41] This is close to the top-of-the-book activity reported for U.S. big-cap stocks in Conrad et al. (2015, Table 1) and about one third of the update frequencies of the e-mini S&P500 (ES) future on ten price levels (Christensen et al., 2013, based on their Fig. 5). It is worth remembering that our quote updates are averages for a single representative instrument of the bucket, not a total of all instruments in the bucket.

[42] This finding is also surprising because the Eurex fines exchange members if their ratios of messages to executions are too large–see https://www.eurex.com/ex-de/rules-regs-de/excessive-system-usage-fee.

[43] See Appendix B for details.

[44] For example, Kandel et al. (1999, p. 235) find a quantity-price elasticity of about 37 based on Israelian IPO auctions, Wurgler and Zhuravskaya (2002, p. 603) report an elasticity between 5 and 12 for U.S. stocks, Kaul et al. (2000, p. 911) report estimates of about 10.5 for stocks traded on the Toronto Stock Exchange, and Dierker et al. (2016, p. 1530) report estimates between 20 and 40 based on Korean stock market data. It is important to note, however, that the estimates are obtained partly by using different methods and different types of data (e.g., share auction data rather than limit order book data). Vijh (1990) also finds that option markets have been deeper than stock markets in the U.S. in the 1980s, in the sense that there is no evidence for option price effects after large option trades.

are in the slightly OTM strike range. Furthermore, we observe that as the probability per time unit of an order being executed increases with rising trading activity, (relative) spreads decrease. Concurrently, the frequency of order book updates increases and market depth expands. Trading is thus associated with liquidity, in line with the empirical literature on order books for stocks (e.g., Chordia et al., 2005).

An important takeaway from Tables 6 and 7 is the heterogeneity across the different moneyness and tenor buckets. As we argue in Section D, one way to read this is that price discovery for options differs across the buckets. The reason is that option prices are determined by multiple state variables, where the sensitivity of option prices to changes of these state variables depends on the options' moneyness and tenor range. Besides the underlying asset, the state variables include the volatility as well as the upside and downside tail risk. Therefore, depending on the moneyness category, liquidity providers in option order books are exposed to informed trading with respect to different state variables, which should impact their bidding behavior in the various option instruments. Inventory risk of market makers may also explain some of the heterogeneity in prices and liquidity across options with different moneyness and tenors, whereas one would expect display and order processing costs or costs of quote monitoring efforts to have effects that depend less on the options' moneyness or tenor.

Table 6: Descriptive order book statistics by moneyness and tenor.

	Put				Call			
	Tenor				Tenor			
Moneyness	[10, 45]	[46, 80]	[81, 120]	[121, 365]	[10, 45]	[46, 80]	[81, 120]	[121, 365]
[−6, −3]	3.13	4.66	6.61	8.65	711.30	916.80	1,121.51	1,210.95
	{0.130}	{0.098}	{0.097}	{0.119}	{0.012}	{0.009}	{0.007}	{0.006}
	⟨120⟩	⟨124⟩	⟨75⟩	⟨45⟩	⟨425⟩	⟨349⟩	⟨241⟩	⟨94⟩
	(190)	(40)	(17)	(47)	(2)	(0)	(0)	(2)
	⟦0.41⟧	⟦0.15⟧	⟦0.07⟧	⟦0.22⟧	⟦0.10⟧	⟦0.04⟧	⟦0.07⟧	⟦0.38⟧
	⌈84⌋	⌈104⌋	⌈NA⌋	⌈64⌋	⌈NA⌋	⌈NA⌋	⌈NA⌋	⌈NA⌋
[−3, −2]	9.63	14.36	18.74	25.86	513.03	657.91	794.57	1,010.54
	{0.054}	{0.038}	{0.043}	{0.056}	{0.014}	{0.010}	{0.008}	{0.008}
	⟨420⟩	⟨382⟩	⟨261⟩	⟨169⟩	⟨720⟩	⟨599⟩	⟨471⟩	⟨240⟩
	(197)	(50)	(23)	(47)	(4)	(0)	(0)	(1)
	⟦1.30⟧	⟦0.47⟧	⟦0.36⟧	⟦0.60⟧	⟦0.48⟧	⟦0.05⟧	⟦0.02⟧	⟦0.10⟧
	⌈65⌋	⌈76⌋	⌈79⌋	⌈57⌋	⌈NA⌋	⌈NA⌋	⌈NA⌋	⌈NA⌋
[−2, −1]	24.99	34.69	43.65	59.12	374.90	472.80	540.44	703.54
	{0.034}	{0.025}	{0.028}	{0.031}	{0.016}	{0.012}	{0.011}	{0.011}
	⟨742⟩	⟨731⟩	⟨644⟩	⟨500⟩	⟨969⟩	⟨825⟩	⟨700⟩	⟨391⟩
	(376)	(109)	(55)	(98)	(28)	(5)	(1)	(1)
	⟦3.99⟧	⟦1.84⟧	⟦1.49⟧	⟦2.93⟧	⟦0.84⟧	⟦0.21⟧	⟦0.29⟧	⟦0.25⟧
	⌈44⌋	⌈51⌋	⌈60⌋	⌈51⌋	⌈11⌋	⌈NA⌋	⌈NA⌋	⌈NA⌋
[−1, 0]	71.63	94.02	114.60	145.33	200.89	255.88	307.84	382.50
	{0.024}	{0.019}	{0.022}	{0.025}	{0.021}	{0.016}	{0.017}	{0.018}
	⟨1,128⟩	⟨1,114⟩	⟨1,015⟩	⟨805⟩	⟨1,221⟩	⟨1,182⟩	⟨1,069⟩	⟨758⟩
	(633)	(203)	(149)	(263)	(102)	(32)	(21)	(32)
	⟦15.19⟧	⟦7.52⟧	⟦8.17⟧	⟦17.11⟧	⟦3.90⟧	⟦1.36⟧	⟦1.67⟧	⟦3.11⟧
	⌈36⌋	⌈45⌋	⌈43⌋	⌈43⌋	⌈30⌋	⌈25⌋	⌈31⌋	⌈34⌋
[0, 1]	199.04	260.22	302.47	360.48	49.51	63.49	76.59	€103.40
	{0.025}	{0.019}	{0.019}	{0.020}	{0.037}	{0.033}	{0.041}	{0.042}
	⟨1,204⟩	⟨1,168⟩	⟨1,031⟩	⟨709⟩	⟨966⟩	⟨1,013⟩	⟨951⟩	⟨747⟩
	(157)	(60)	(77)	(99)	(828)	(216)	(172)	(228)
	⟦9.23⟧	⟦4.08⟧	⟦8.53⟧	⟦16.92⟧	⟦11.56⟧	⟦4.91⟧	⟦4.82⟧	⟦9.45⟧
	⌈36⌋	⌈33⌋	⌈35⌋	⌈44⌋	⌈37⌋	⌈45⌋	⌈39⌋	⌈43⌋
[1, 2]	385.38	452.45	525.06	671.90	3.57	4.51	5.59	7.59
	{0.023}	{0.018}	{0.014}	{0.013}	{0.181}	{0.162}	{0.184}	{0.191}
	⟨576⟩	⟨438⟩	⟨321⟩	⟨169⟩	⟨153⟩	⟨103⟩	⟨70⟩	⟨54⟩
	(32)	(13)	(12)	(5)	(361)	(72)	(37)	(52)
	⟦5.49⟧	⟦1.93⟧	⟦2.98⟧	⟦1.41⟧	⟦0.59⟧	⟦0.21⟧	⟦0.12⟧	⟦0.24⟧
	⌈31⌋	⌈NA⌋	⌈NA⌋	⌈NA⌋	⌈53⌋	⌈71⌋	⌈62⌋	⌈61⌋
[2, 3]	522.72	NA	NA	NA	NA	NA	NA	NA
	{0.019}	{NA}	{NA}	{NA}	{NA}	{NA}	{NA}	{NA}
	⟨284⟩	⟨111⟩	⟨41⟩	⟨20⟩	⟨17⟩	⟨11⟩	⟨10⟩	⟨10⟩
	(6)	(1)	(0)	(0)	(21)	(1)	(0)	(1)
	⟦1.19⟧	⟦0.20⟧	⟦0⟧	⟦0.03⟧	⟦0.01⟧	⟦0⟧	⟦0⟧	⟦0⟧
	⌈NA⌋	⌈NA⌋	⌈NA⌋	⌈NA⌋	⌈80⌋	⌈NA⌋	⌈NA⌋	⌈NA⌋

Notes: The table shows the average option price in euro, {relative spread in percent}, ⟨number of order book updates in a 1 minute interval⟩, (daily number of trades), ⟦daily trading euro volume in millions⟧ per bucket, including the contract value of 10, and ⌈lot size per trade⌋. The figures in a single bucket are computed from all instruments falling into the respective bucket and thus are derived from multiple order books of different instruments. Therefore, they are to be interpreted as being the average statistic of the order book of a *representative* instrument in a given bucket. Moneyness is defined as $\log(K/F)/(\sigma\sqrt{\tau})$.

Table 7: Elasticities in order books by moneyness and tenor.

Panel A: Puts

	Bid				Ask			
	Tenor				Tenor			
Moneyness	[10, 45]	[46, 80]	[81, 120]	[121, 365]	[10, 45]	[46, 80]	[81, 120]	[121, 365]
[−6, −3]	−5.7	−8.4	−9.8	−12.3	7.6	10.2	12.1	14.6
[−3, −2]	−19.7	−25.7	−28.7	−34.7	16.8	20.5	25.5	38.7
[−2, −1]	−47.9	−63.1	−51.3	−55.7	51.4	71.7	56.5	58.1
[−1, 0]	−118.0	−134.6	−113.0	−110.3	120.8	132.4	115.9	110.3
[0, 1]	−102.2	−116.1	−101.4	−119.5	104.9	118.3	109.1	130.0
[1, 2]	−61.7	−69.6	−64.5	−94.2	62.1	64.0	63.6	93.5
[2, 3]	−59.6				56.1			

Panel B: Calls

	Bid				Ask			
	Tenor				Tenor			
Moneyness	[10, 45]	[46, 80]	[81, 120]	[121, 365]	[10, 45]	[46, 80]	[81, 120]	[121, 365]
[−6, −3]	−99.7	−127.6	−74.3	−109.4	108.8	124.9	72.5	111.3
[−3, −2]	−89.5	−117.1	−99.6	−108.6	93.9	116.5	93.8	110.3
[−2, −1]	−108.7	−115.4	−118.1	−115.0	113.8	120.0	115.6	124.5
[−1, 0]	−107.8	−124.2	−116.6	−132.7	110.5	125.1	112.7	131.7
[0, 1]	−84.8	−91.3	−77.6	−82.0	90.7	95.3	81.6	88.2
[1, 2]	−10.0	−9.2	−7.4	−8.7	9.3	8.2	7.3	9.3
[2, 3]					1.8	1.1	2.1	1.7

Notes: Higher elasticities correspond to darker blue color. The figure in a single bucket is computed from all instruments falling into the respective bucket and thus is derived from multiple order books of different instruments. Therefore, it is to be interpreted as being the average statistic of the order book of a *representative* instrument in a given bucket. The grey fields denote NAs (in these cases, a bucket has fewer than 20,000 obs). Moneyness is defined as $\log(K/F)/(\sigma\sqrt{\tau})$.

E.2 Market depth and spreads over the sample period

Figures 7 and 8 show the evolution of the liquidity conditions for put and call options in different tenor buckets. The figures are organized in a 2×2 layout, where each subplot consists of an upper panel, showing the evolution of market depth, and a lower panel, reporting relative spreads. To differentiate market depth and spreads within different moneyness buckets, we use darker colors to represent options that are further OTM. Market depth is measured in terms of the quantity-price elasticity where the elasticity has a positive sign on the ask side and a negative sign on the bid side. The grey bar indicates the time period from March 12 to 23, on which we focus particularly when analyzing the effect of monetary policy decisions using intraday data in Section 4.

In Figures 7 and 8, we use the simple forward moneyness, defined as $\log(K/F^{\tau})$ where K is the strike, F the forward, and τ tenor. We prefer the forward moneyness here because it is more natural to observe how the elasticity and spreads of options of a fixed strike distance to ATM vary over time.[45] For comparison, we also provide the corresponding Figures 9 and 10 based on the standardized moneyness.

We first discuss the evolution of liquidity for puts in detail and then compare it briefly to the evolution of liquidity for calls. Starting our analysis with the short-dated puts in the upper left of Figure 7, we observe that in January and February only the very near-the-money options offered a high amount of liquidity, with an elasticity close to or exceeding 100. Slightly ITM puts were even more liquid than slightly OTM options, albeit, as seen below, at the expense of higher spreads. OTM put options in the forward moneyness range of -30% to -5% were very illiquid. For the period of January and February, similar observations apply to other tenor ranges: near-the-money options offer the highest market depth. For options with a larger tenor, however, OTM options gradually offer more depth.[46] Furthermore, the spreads tend to become more similar

[45] The buckets of forward moneyness are $[-0.3, -0.1]$, $[-0.1, -0.05]$, $[-0.05, 0]$, $[0, 0.05]$ for puts and $[0.3, 0.1]$, $[0.1, 0.05]$, $[0.05, 0]$, $[0, -0.05]$ for calls, here ordered from OTM to progressively ATM strikes. We do not consider deeper ITM puts because of lack of data. For the remaining combinations of strike buckets and tenors, for which we do not observe enough data in the order books on certain days (see Appendix A), gaps are visible in the time series. See, for example, Figure 8.

[46] This is consistent with Table 7 because the standardized moneyness metric covers a broader strike

the larger the tenor.

When the COVID-19 crisis struck markets in early March, its impact on the order books was fourfold: (*i*) puts in moneyness ranges with high market depth prior to the crisis saw market depth subside, and more so the shorter the tenor; (*ii*) in contrast, initially low market depth put strike ranges saw market depth expand significantly, and more so the shorter the tenor; (*iii*) spreads doubled or even tripled, and they increased more the larger the tenor; (*iv*) spreads of far OTM options declined, at least for tenors up to 120 days.

Thus, rather than a straightforward liquidity contraction, the initial impact of the pandemic shock on option markets was very nuanced. Both compressions *and* expansions of liquidity occurred along the tenor-moneyness dimensions of the option price surface even at times of the highest market distress. At the same time, the relative spreads increased ATM and slightly OTM, but decreased for far OTM puts, particularly those with short to medium tenors. The significant reduction in relative spreads of OTM puts reflects that their prices have become disproportionately higher compared to the prices of ATM and slightly OTM options. As we discuss in Section 4, we relate this phenomenon to a substantial increase in downside tail risk.

By mid-March, we observe a recovery in market depth for strike ranges that had experienced a decline in liquidity. As a result, market depth converged across various strike ranges, with elasticities returning to levels above or close to 100. Additionally, the spreads, which had exhibited significant heterogeneity in January and February, also converged. They remained elevated, however, or even increased further, notably for long-tenor puts, whose spreads reached their peaks within the grey bar, the period of highest market stress. It is not until the end of March that we observe a decrease in spreads and a further increase in market depth. Recalling Figure 2, we note that the days with the highest trading volume coincide with the days of lowest market depth and highest spreads.

At the end of April, the put elasticity peaked, being close to or even above 200, and relative spreads were lowest, largely below 2%. The extraordinary turnover, however,

range, the larger the tenor and the higher the IV.

had already subsided by this time (see Figure 2). Towards the end of the sample period in June, the overall elasticity remained persistently high and spreads relatively low. Interestingly, the bid and the ask side evolved in almost perfect symmetry, suggesting that both the demand and supply of puts developed in lock-step. In contrast, Haddad et al. (2021), Kargar et al. (2021), and O'Hara and Zhou (2021) document a sharp rise in the demand of liquidity in the secondary corporate bond market and the unwillingness of dealers to supply it.

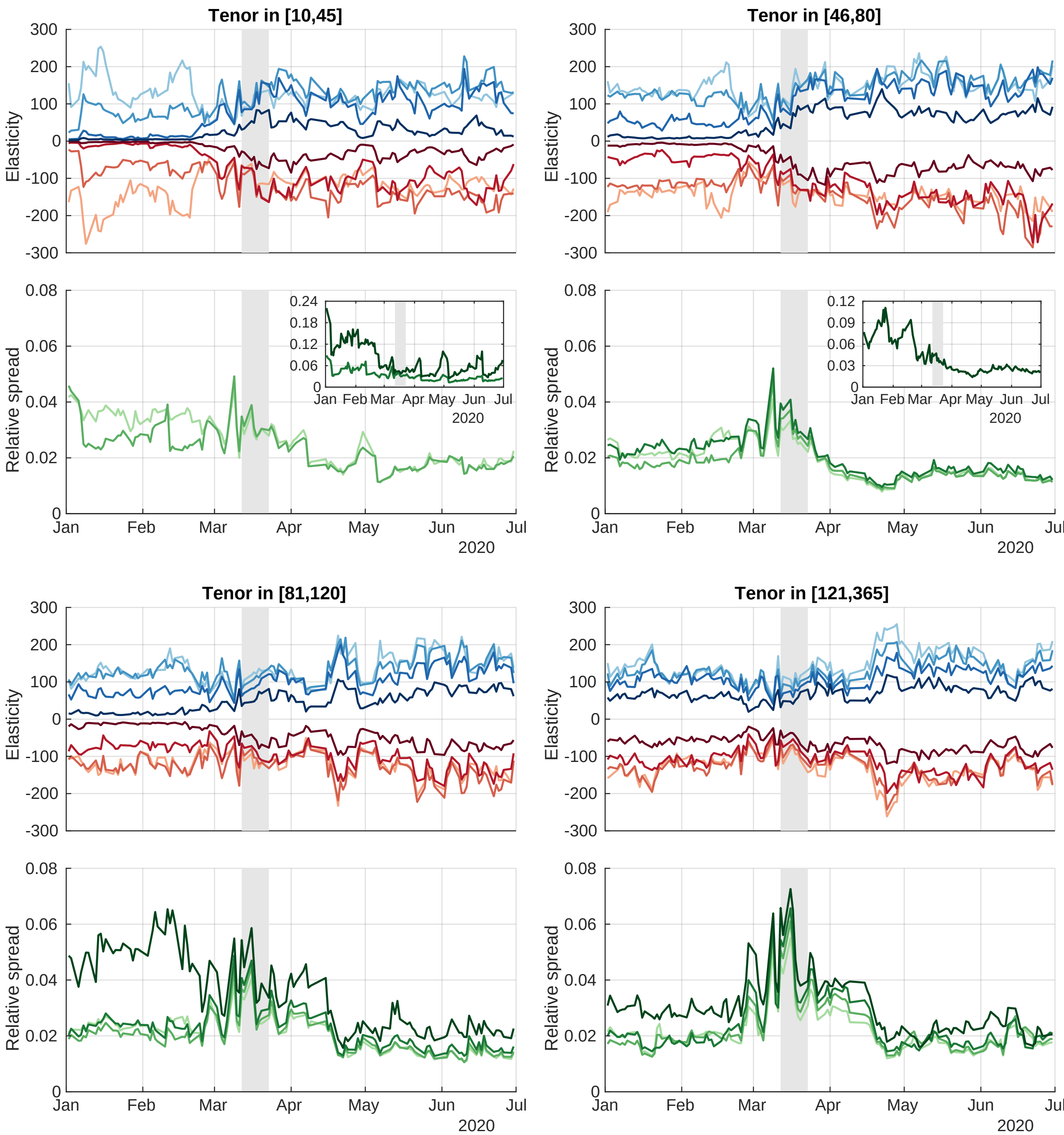
Inspecting the evolution of the liquidity of call options in Figure 8, we find similar patterns as described for puts with two notable differences. First, in line with Table 7, the ATM market depth is somewhat lower than for puts, and the growth in market depth starting in March is more moderate for calls than for puts. For options with tenors between 81 to 365 days in the figure, market depth of the far OTM calls increased much less than for far OTM puts. Second, the spreads of far OTM calls decreased from their elevated levels; data limitations, however, sometimes prevented us from calculating them–see, e.g., the insets in the upper right or lower left panels of Figure 8. Furthermore, the OTM call spreads tend to be higher and more heterogeneous than the corresponding OTM put spreads.

Figures 9 and 10 illustrate the market depth and spreads if we classify options into moneyness buckets based on the standardized moneyness metric. The main conclusions are largely similar. We observe a significant contraction in liquidity provision during the crisis in March 2020. The immediate expansion of liquidity at the height of the crisis for OTM strikes, observed in the figures based on the forward moneyness metric, is less visible. This is because, based on the standardized moneyness metric, the strikes falling into the far OTM bucket are much lower due to the elevated levels of IV in March. This is also significant in the context of the evolution of relative spreads OTM puts. Notably, these spreads do *not* decrease in the figures when using the standardized moneyness metric. Instead, they remain stable until March and then exhibit a sharp increase from March to mid-April. We find that, for both moneyness metrics, liquidity increased after April 2020. Even for far OTM strikes, liquidity increased to a higher level than before the crisis.[47]

To sum up, we document a quite heterogeneous response of spreads and market depth across options, differing by forward (standardized) moneyness and tenor, and across time. Market microstructure models suggest that elevated levels of volatility may either increase spreads due to the higher risk of liquidity providers being picked off more easily (Foucault, 1999) or decrease spreads as providers seek to mitigate execution risk (Foucault et al., 2013, ch. 6.4.3). Figures 7 to 10 show that higher levels of volatility can be associated with lower spreads, too. Similarly, we observe significant expansions and contractions of market depth over the sample period. These patterns also may be generated by changes in the asymmetry of information regarding the state variables of option prices, or the inventory risk of market makers for options with different moneyness and tenor, during the pandemic.[48] We further investigate such possible mechanisms in Section 4, in which we use intraday data to analyze the effects of monetary policy on the liquidity of option markets.

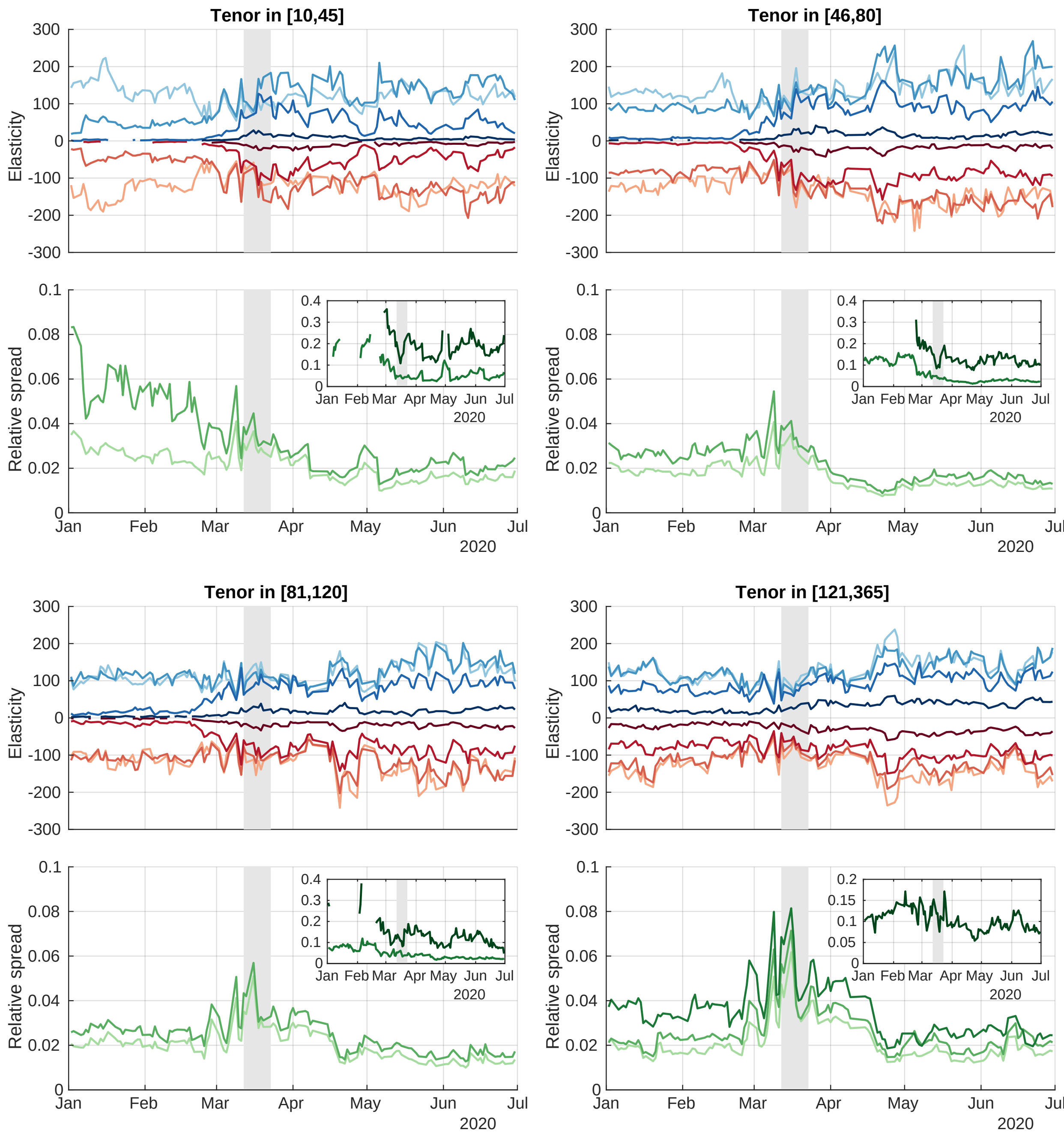
[47]Similarly, Wei and Zheng (2010) report that trading activity shifts towards OTM options during high-volatility periods, leading to reduced spreads for OTM options. Their findings are based on U.S. stock option data from 1996 to 2007.

[48]The time series on trading volumes in Figure 2 suggest that transaction costs have not been the main driver behind the observed changes in option market liquidity. If transaction costs include a fixed component and the costs are financed per trade, the costs should be negatively correlated with trading volume. Thus, the high spreads in March 2020 and the lower spreads and higher elasticities observed from April 2020 onwards do not seem to result from fixed transaction costs and changes in trading volumes but rather from other channels, such as asymmetric information and inventory risk.



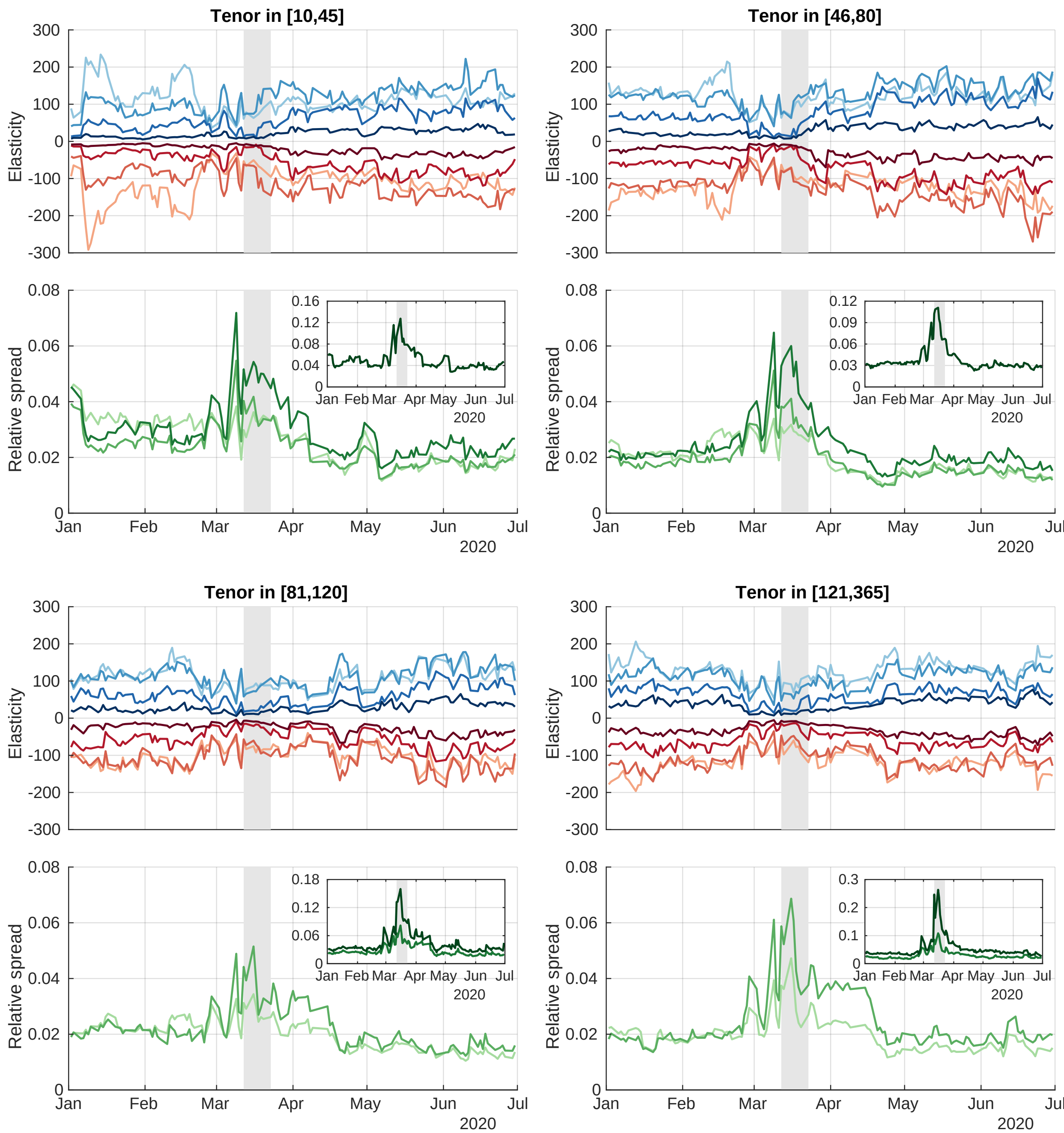
Sources: Eurex and own calculations. *Notes:* Daily data. Elasticities and spreads of puts on the fwd moneyness with buckets being defined as [-0.3,-0.1], [-0.1,-0.05], [-0.05,0], [0,0.05]. The darker the color, the more OTM; the lighter the color, the more ITM. Gaps indicate numbers that could not be computed due to insufficient liquidity (less than 100 observations). The grey bar indicates the time period from March 12 to 23, for which we report results in the main text when we analyze the effect of monetary policy decisions using intraday data in Section 4.

Figure 7: Put elasticities and put spreads over time, across options with different forward moneyness and tenor



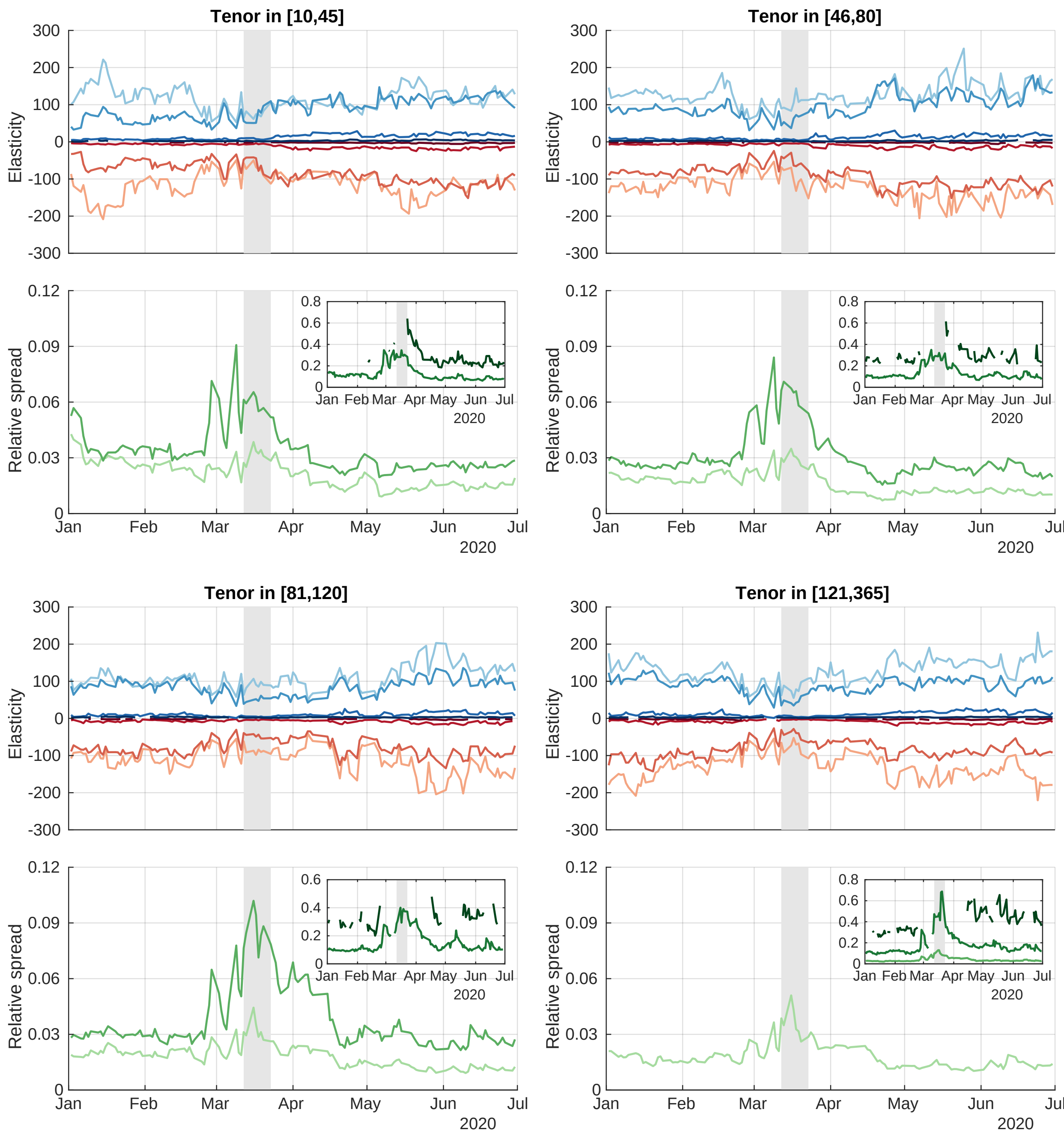
Sources: Eurex and own calculations. *Notes:* Daily data. Elasticities and spreads of calls on the fwd moneyness with buckets being defined as [0.3,0.1], [0.1,0.05], [0.05,0], [0,-0.05]. The darker the color, the more OTM; the lighter the color, the more ITM. Gaps indicate numbers that could not be computed due to insufficient liquidity (less than 100 observations). The grey bar indicates the time period from March 12 to 23, for which we report results in the main text when we analyze the effect of monetary policy decisions using intraday data in Section 4.

Figure 8: Call elasticities and call spreads over time, across options with different forward moneyness and tenor



Sources: Eurex and own calculations. *Notes:* Daily data. Elasticities and spreads of puts on the std moneyness with buckets being defined as [-3,-1.5], [-1.5,-1], [-1,0], [0,1]. The darker the color, the more OTM; the lighter the color, the more ITM. Gaps indicate numbers that could not be computed due to insufficient liquidity (less than 100 observations). The grey bar indicates the time period from March 12 to 23, for which we report results in the main text when we analyze the effect of monetary policy decisions using intraday data in Section 4.

Figure 9: Put elasticities and put spreads over time, across options with different standardized moneyness and tenor



Sources: Eurex and own calculations. *Notes:* Daily data. Elasticities and spreads of calls on the std moneyness with buckets being defined as [3,1.5], [1.5,1], [1,0], [0,-1]. The darker the color, the more OTM; the lighter the color, the more ITM. Gaps indicate numbers that could not be computed due to insufficient liquidity (less than 100 observations). The grey bar indicates the time period from March 12 to 23, for which we report results in the main text when we analyze the effect of monetary policy decisions using intraday data in Section 4.

Figure 10: Call elasticities and call spreads over time, across options with different standardized moneyness and tenor

E.3 Insights from market microstructure theory

In our main analysis, we connect the insights derived from option pricing theory and the microfoundations of market liquidity as proposed by market microstructure theory. Considering the insight from both literatures jointly, allows us to interpret the stylized facts of the option order books and the impact of the monetary policy decisions discussed in Section 4.

Asymmetric information. Asymmetric information models of stock order books assume the presence of uninformed liquidity traders and informed traders, who know the fundamental value of the traded stock (Glosten and Milgrom, 1985). Liquidity providers do not know in advance who they are trading with. Expanding on the ideas of Section D, we note that in option order books informed trading may not only occur in terms of the underlying asset's fundamental value as in stock order books but also in relation to the volatility state and the upside and downside tail risk. Indeed, a significant number of studies establishes evidence of informed trading in option markets (see, inter alia, Chakravarty et al., 2004, Pan and Poteshman, 2006, Muravyev, 2016, Bernales et al., 2020, Chen et al., 2022). Because we focus on index options rather than single stock options, the information asymmetry relates to market events like a possible crash rather than changes in the valuation of a single stock.

Informed trading models suggest that spreads increase in the likelihood of trading with an informed trader and the expected order size (Glosten and Milgrom, 1985, Lin et al., 1995). This is because informed traders have an incentive to submit large orders despite a possible price impact to capitalize on their private knowledge. The top-of-book liquidity provider takes this into account, resulting in a non-zero bid-ask spread even with zero display and order processing costs. Additionally, market depth declines with the informativeness of the order flow (Foucault et al., 2013, p. 202).

Our findings for OTM options in Appendix E.1 are consistent with these predictions. Indeed, measured relative to the option price, spreads of OTM puts and OTM calls are large. Moreover, we document that the average trade size increases the farther the option is OTM. Taken together, both observations suggest that the trade flow in OTM options is very informative. According to our illustrations in Section D, trading in short-term OTM puts (OTM calls) could be informative particularly about downside (upside) tail risk. Furthermore, informed traders may find trading far OTM options appealing due to the substantial leverage these options provide.

As regards ATM options, the average trade size is clearly in the lower quantiles of the trade size distribution while market depth is high. In this case, order book models predict that the trade flow contains a high proportion of uninformed trade flow. Indeed, market participants seeking to hedge gamma or volatility exposures necessarily do so near-the-money because these risks can be only hedged effectively using ATM options.[49] Based on Section D, informed trading in ATM options with short tenor could be related to the state of volatility.[50]

For ITM puts, the predictions of order book models are ambiguous given that the stylized facts reveal that both market depth and order size retreat. Remarkably, ITM calls exhibit a market depth that is close in terms of magnitude to that of the most actively traded strikes near-the-money, despite having a very low trading intensity. The high market depth, together with small relative spreads and small trade sizes, may speak for a low intensity of informed trading in ITM calls, much in contrast to the trade flow of ITM puts. Note, however, that ITM options, measured by the trading volume, have the least economic relevance in our data.

Inventory risk and replication costs of market makers. Stoll (1978) proposed that risk-averse market makers aim to avoid large balance sheets due to the potential for inventory risk resulting from unexpected changes in the market value of their balance sheet components. Inventory risk models predict that market makers require a premium for allowing their inventory to deviate from the optimal level, and their bidding behavior depends on the deviation of their holdings from that level (Amihud and Mendelson,

[49] The option gamma captures the second derivative of the option price with respect to the value of the underlying.

[50] Informed trading about the fundamental value appears unlikely because ATM options provide lower leverage and are more exposed to volatility risk than OTM options.

1980, Ho and Stoll, 1981). For option markets, inventory risk may be more relevant than for stock markets because of imperfect hedging and substantial model risk faced by option traders (Jameson and Wilhelm, 1992, Green and Figlewski, 1999, Battalio and Schultz, 2011). Empirical evidence supports this perspective (Muravyev, 2016).

The evidence presented in Section E.1 is consistent with key predictions of inventory risk models. If (far) OTM puts and calls are more exposed to non-hedgeable forms of risk, such as jump risk, they imply higher inventory risk. The market maker then bids less aggressively so that spreads are wider and market depth lower. The associated larger lot sizes, in which OTM options trade, further increase the inventory risk for market makers. In contrast, ITM options, whose main risk is the change in the underlying asset because their delta is close to one, can be hedged efficiently by offsetting positions in the EURO STOXX 50 future.[51] In addition, ITM options require only infrequent adjustments of the replicating portfolio because they have a low gamma. Hence, market makers may incur smaller replication costs (Leland, 1985) and thus set small spreads and provide high market depth, as we document.

Display and order processing costs. While order submission and order processing costs give rise to a bid-ask spread (Glosten, 1994, among others), they do not explain the observed heterogeneity across options, because they are unlikely to differ by strike and tenor or by option type. Moreover, fixed transaction costs of trading and returns to scale cannot explain why liquidity in option markets decreased when trading volumes increased at the beginning of the COVID-19 crisis (see Figure 2) and then increased when trading volumes decreased.

Costs of quote monitoring efforts. Foucault et al. (2003) suggests that monitoring news arrivals is costly because it requires human attention. Market makers must balance the cost of monitoring with the potential benefits, as misaligned quotes can be exploited. Monitoring generates a positive and a negative externality, because competing market makers free-ride on the efforts of others who monitor quotes, while the actual adjustment

[51]The delta captures the sensitivity of the option price to changes of the underlying asset.

of quotes exposes their stale quotes.

This model offers another angle for interpreting our stylized facts. Section D suggests that the externalities are largest when option prices are most elastic with respect to changes of state variables. For example, short-dated OTM options are highly elastic to changes in jump risk. Market makers can react to this by increasing their monitoring efforts, or by quoting wider spreads and providing lower market depth if they exert less monitoring effort. If we consider the number of quote updates as an indicator of monitoring efforts, this suggests low monitoring efforts for OTM options, where spreads are wide, market depth low, and the frequency of quote updates small. This is much in contrast to markets for ATM options, which exhibit the opposite characteristics. Concerning ITM options, they are likely to be associated with high monitoring efforts because their prices closely follow the underlying asset's movements. This may explain the high number of quote updates we observe for ITM options. Thus, the heterogeneity of market liquidity and quote updates may result from optimal monitoring efforts by liquidity providers.

F Evidence on the effect of monetary policy announcements and other events

F.1 The events

We analyze intraday patterns on the following days.

- ECB monetary policy decisions
  - January 23 (13:45 hrs announcement, 14:30 hrs press conference): kept policy rates unchanged; continued asset purchases of 20 bn euro per month.
  - March 12 (13:45 hrs announcement, 14:30 hrs press conference): longer-term refinancing operations (LTROs), targeted long-term refinancing operations (TLTRO III), asset purchases; statement: "we are not here to close spreads."

- March 18 (after close of trading): Pandemic Emergency Purchase Program (PEPP) of 750 bn euro
- April 30 (13:45 hrs announcement, 14:30 hrs press conference): further liquidity provision measures: non-targeted pandemic emergency longer-term refinancing operations (PELTROs)
- June 4 (13:45 hrs announcement, 14:30 hrs press conference): increase of PEPP by 600 bn euro

• Other selected ECB press releases
  - March 20 (10:00 hrs EDT = 15:00 hrs CET): further US-$ liquidity provisions, coordinated with other central banks (announcement time of Federal Reserve)
  - April 7 (17:45 hrs CEST): temporary collateral easing measures

• Federal Reserve: Federal Open Market Committee meetings

  We account for the different timing of the switch from standard to daylight saving time, which occurred on March 8, 2020 in the U.S. and March 29, 2020 in Europe.

  - March 3 (10:00 hrs EST = 16:00 hrs CET): decrease of policy rate by 50 bp to 1 – 1.25%
  - March 15 (17:00 hrs EDT = 22:00 hrs CET): decrease of policy rate by 100 bp to 0 – 0.25%; quantitative easing through purchasing at least 700 bn US-$ of treasury bills and mortgage-backed securities
  - March 19 (9:00 hrs EDT = 14:00 hrs CET): additional liquidity arrangements (swap lines) for other foreign central banks
  - March 23 (8:00 hrs EDT = 13:00 hrs CET): announce primary and secondary market corporate credit facilities (PMCCF and SMCCF); extend range of municipal securities that qualify for commercial paper funding facility and money market funding facility; continue with asset purchases "in amounts needed"
  - March 31 (8:30 hrs EDT = 14:30 hrs CEST): temporary repurchase facilities for foreign and international monetary authorities

- April 29 (14:00 hrs EDT = 20:00 hrs CEST): continued support of economy using full range of tools
- June 10 (14:00 hrs EDT = 20:00 hrs CEST): "increase holdings of Treasury securities and agency residential and commercial mortgage-backed securities at least at the current pace to sustain smooth market functioning"

- Other selected press releases of the Federal Reserve
  - March 17 (10:45 hrs EDT = 15:45 hrs CET): announce establishment of commercial paper funding facility (CPFF) for liquidity of credit to households and businesses
  - March 17 (18:00 hrs EDT = 23:00 hrs CET): announce establishment of primary dealer credit facility (PDCF) to support credit to households and businesses by allowing primary dealers to pledge a broad class of assets as collateral
  - March 18 (23:30 hrs EDT = March 19 4:30 hrs CET): establish money market mutual fund liquidity facility (MMLF) to increase liquidity of money markets
  - April 9: (8:30 hrs EDT = 14:30 hrs CEST): establish municipal lending facility; extend PMCCF and SMCCF
  - April 30 (17:15 hrs EDT = 23:15 hrs CEST): expanded access to Paycheck Protection Program Liquidity Facility (PPPLF) for additional lenders, and expanded pledgable collateral

- Fiscal measures
  - March 13 (12:30-12:45 hrs): secretaries Altmaier and Scholz announce the fiscal *bazooka* for Germany; other EU countries announce similar measures in mid March
  - March 19 (after close of trading): the U.S. unveil trillion dollar fiscal stimulus signed into law on March 27 as CARES act
  - April 9 (after close of trading): EU finance ministers settle on coronavirus support package to be agreed on EU summit on April 23

  - April 23 (after close of trading): EU summit passes 540 bn coronavirus support package leaving details for a recovery plan to be decided
  - May 18 (16:00 hrs): Macron and Merkel announce joint proposal for European recovery fund of 500 bn euro
  - Outside of our sample period, mentioned for completeness:
    July 21 (early morning press conference at 6:00 hrs): the EU heads of state reach an agreement on the 750 bn euro pandemic recovery plan NextGenerationEU on July 21, 2020

- Other events
  - March 11 (after close of trading): WHO declares pandemic; Trump announces travel ban from continental Europe to U.S.
  - May 5 (10:00 hrs): German constitutional court rules that the ECB decisions on public sector purchase programs since 2015 (except the PEPP) exceed EU competences
  - Outside of our sample period, mentioned for completeness:
    July 2: German parliament concludes that ECB asset purchases have been proportionate after ECB allowed the Bundesbank to share classified documents with the German government and parliament on June 26; previous deliberations on the proportionality as documented in the minutes of the ECB monetary policy meeting on June 3-4

We now illustrate the intraday effects of the monetary policy decisions, on which we focused in the main text. The graphical evidence complements the effects summarized in Table 1.

F.2 Intraday evidence for March 12, 2020

The left column of Figure 11 illustrates the intraday effects of the ECB announcement and subsequent press conference on March 12. The figure shows large effects on the value of the underlying asset (purple color, top panel in the left column), its implied volatility (orange color, top panel in the left column), and tail risk (second panel in the left column). The figure displays the coefficients γ_i estimated for the considered dependent variables, as specified in (1), except for the value of the underlying, for which we plot the log price, normalized by the value in the benchmark time interval of 10:00-10:45 hrs on the event day. The dashed vertical line in the figures illustrates the time of the respective monetary policy announcement (between days if the announcement occurred after the close of trading). The grey area illustrates the time of the subsequent press conference if such a press conference took place. The blue shaded areas illustrate the pre- and post-event windows, on which the estimates in the main text are based.

Figure 11 shows that the value of the underlying decreased by 0.06 log points (approximately 6%) until the end of the trading day relative to the benchmark time interval 10:00-10:45 hrs on the event day. The implied volatility increased by 8 percentage points (pp). As illustrated in Figure 1, volatility increased strongly in March 2020 to levels previously observed during the global financial crisis 2007/2008.[52] The unexpected component of the monetary policy decision on March 12 contributed to this increase with a 10 pp increase on the event day itself, starting from a level of 0.56 for the implied volatility of the considered ATM options with a tenor of 45 days.

The downside left-tail risk, as measured by the price of far OTM put options with short tenor, increased by more than 0.5 log points (approximately 50%). Interestingly, the second panel (left column) in Figure 11 shows that the ask price of far OTM put options with short tenor increased more strongly on impact than the bid price right after the announcement. This indicates that the pronounced rise in volatility, observed in the top panel of Figure 11, could have led to heightened market demand for put options as protection against downside risk and/or increased compensation required by market makers to sell these options. Consequently, this widened the spread of far out-of-the-money (OTM) put options, thereby reducing liquidity in the market for these options.

We assess the downside tail risk shown in Figure 11 by focusing on OTM put options with a moneyness of −2.5. Figure 12 justifies this choice of moneyness by demonstrating

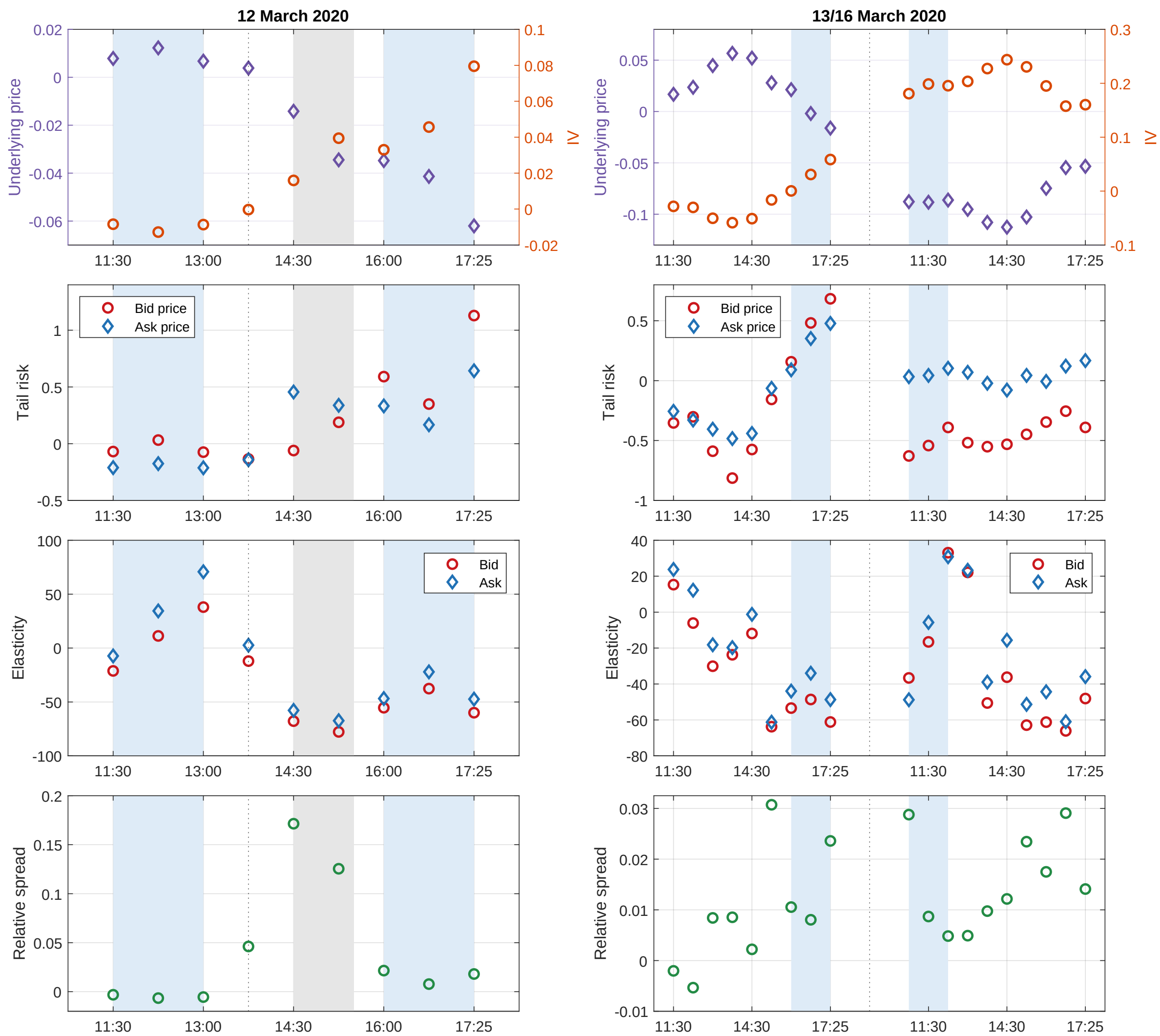
[52] See https://qontigo.com/index/v2tx/

that the directional move in the value of the underlying following the ECB announcement pushed far OTM puts further near-the-money. This shift resulted in options with a standardized moneyness below −3 disappearing by the end of the trading day. Reporting changes of OTM put options at a moneyness of −2.5 in Figure 11 ensures that we observe prices for these OTM put options throughout the respective trading day for the monetary policy decisions considered in this section. The exception is the monetary policy decision on March 18 analyzed further below, for which we need to consider a moneyness of −1.

How did the ECB announcement on March 12 affect liquidity? Focusing on put options with a tenor between 10 and 45 days and standardized moneyness in the interval $[-1, 0]$, the bottom panel (left column) of Figure 11 shows that the spread temporarily increased by more than 10 pp during the announcement and by about 2 pp after the press conference towards the end of the trading day. The panel of Figure 11 in the third row of the left column shows that market depth in terms of the order book elasticity decreased by 50 pp both on the bid and ask side after the ECB's announcement. Because elasticities on the ask and bid side are both expressed in absolute terms, a smaller value implies lower market depth. Figure 11 shows that market depth increased briefly by 50 pp prior to the announcement without any movements in the spread, indicating a short-lived increase in market depth an hour before the announcement.

One possible explanation for the decrease in liquidity following the ECB announcement is that market participants sought protection against potentially better-informed traders, especially when the state variables determining option prices underwent significant changes, as documented in Figure 11.

Inspecting bid and ask prices for short-tenor put options with different standardized moneyness.– Figure 12 shows how bid and ask log prices for put options with a tenor of 1 day increased after the monetary policy decision on March 12. The figure displays the bid and ask log prices at 12:00 hrs as a benchmark in grey color. Upward facing triangles denote the bid log price and downward facing triangles denote the ask log price. Triangles in lighter red or grey denote observed log prices whereas triangles in darker red or grey

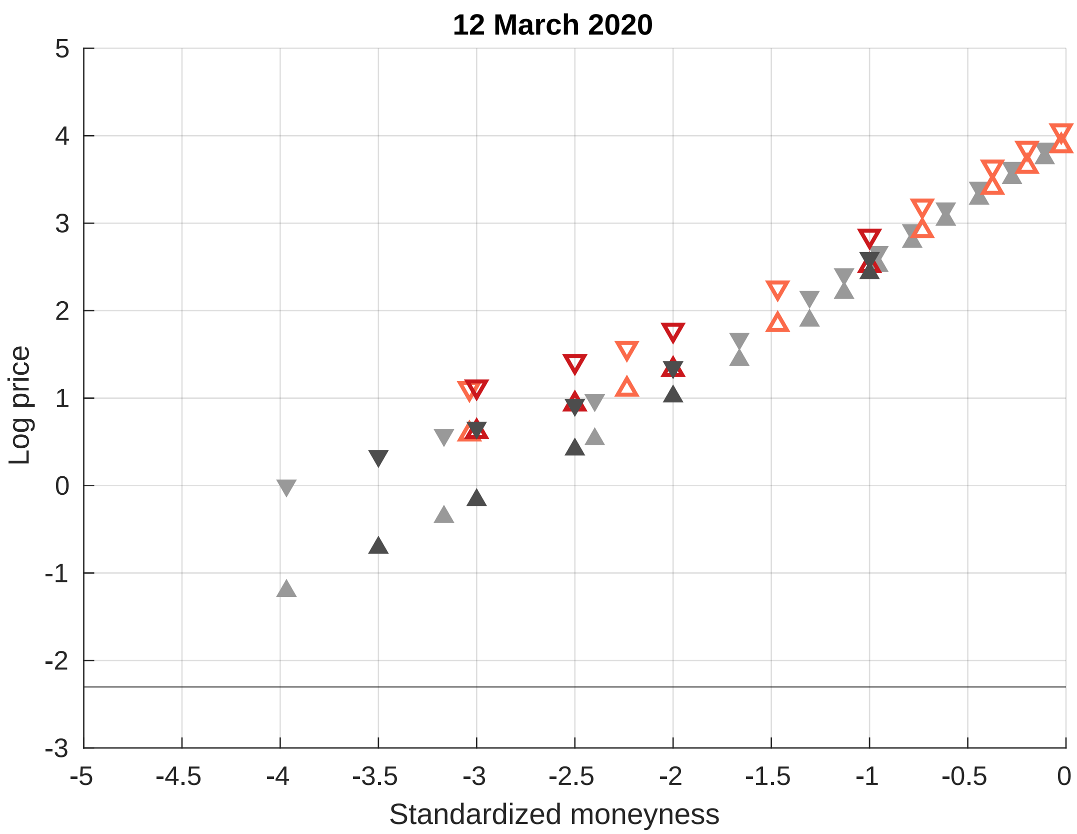


Sources: Eurex. *Notes:* The dashed vertical line illustrates the time of the respective monetary policy announcement, and the grey area illustrates the time of the subsequent press conference if such a press conference took place. The blue shaded areas illustrate the pre- and post-event windows, on which the estimates in the main text are based. The effect on tail risk is based on puts with short tenor between 1 and 7 days and a standardized moneyness of −2.5. The implied volatility is computed based on ATM options with a tenor of 45 days, averaged across puts and calls. The figure displays the coefficients γ_i of the estimated specification (1). Elasticities on the ask and bid side are both in absolute terms so that a smaller value implies less market depth. The effect on spreads and elasticities is reported for put options with a tenor between 10 and 45 days and a standardized moneyness $[-1,0]$. The benchmark interval is 10:00-10:45 hrs on March 12 (left column) and March 13 (right column). The coefficient for each 45-minute interval is depicted in the figures at the end of the respective interval.

Figure 11: The effect of the monetary-policy announcements on March 12 and 15 on option price states and option market liquidity

denote the values interpolated on the moneyness gridpoints, e.g., −3 and −2.5.

Figure 12 demonstrates the increase in option prices across various degrees of moneyness following the ECB's announcement on March 12. Additionally, it reveals that the substantial decline in the value of the underlying after the announcement moved far OTM options further into the money, implying that options with a standardized moneyness below −3 vanish from the order books.



Sources: Eurex. *Notes:* Bid and ask log prices for put options with a tenor of 1 day. The grey triangles denote the benchmark bid and ask log prices at 12:00 hrs on March 12. Upward facing triangles denote the bid log price and downward facing triangles denote the ask log price. The light grey prices are the observed prices and the dark grey prices are the interpolated prices on the moneyness gridpoints, e.g., −3 and −2.5. The red triangles denote the bid and ask log prices at 15:30 hrs. The light red prices are the observed prices and the dark red prices are the interpolated prices.

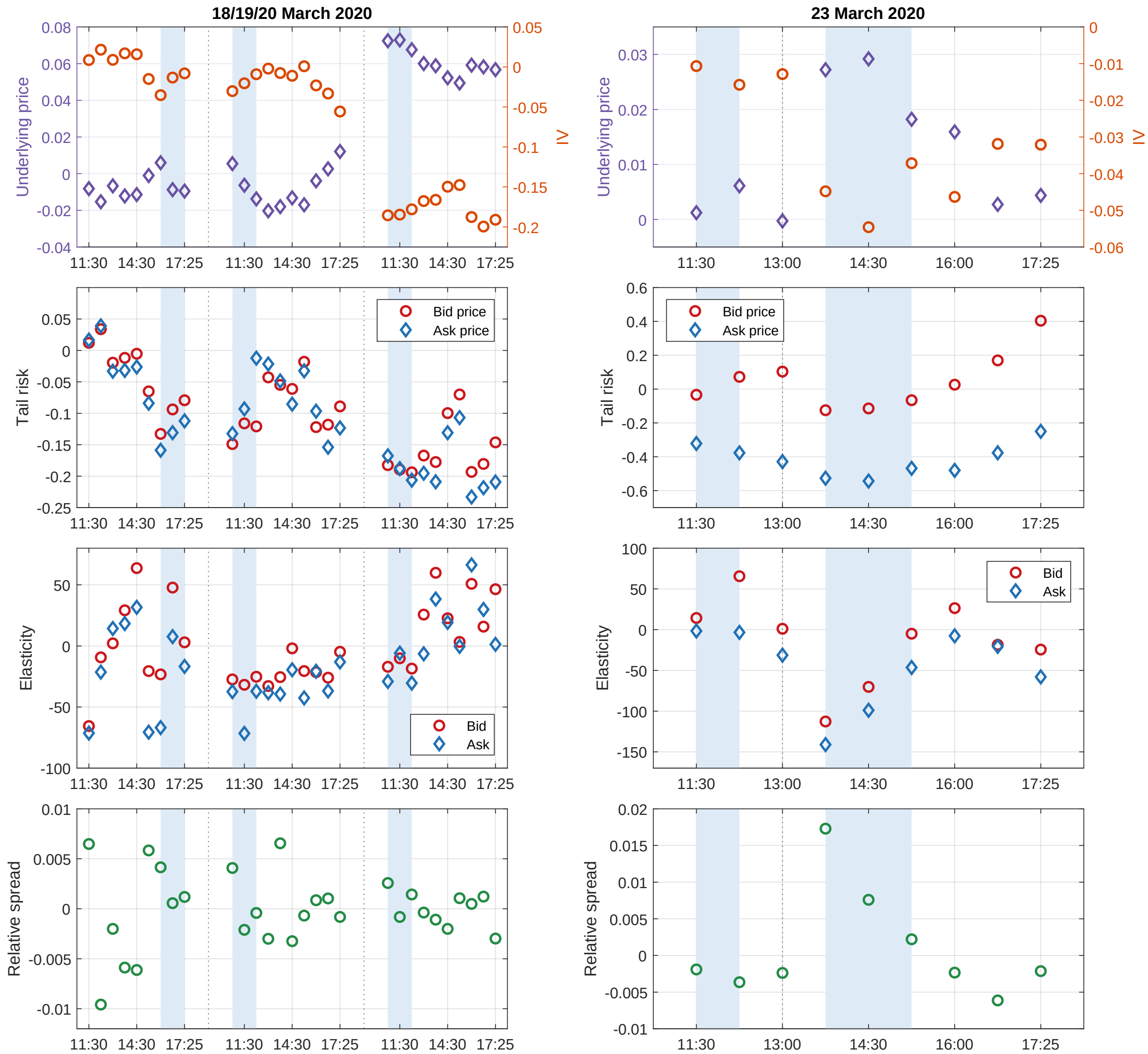
Figure 12: The effect of the ECB's monetary-policy announcement on March 12 on bid-ask option prices as a function of moneyness

F.3 Intraday evidence for March 13-16, 2020

Qualitatively, the announcement of the Fed on March 15 had similar effects as the ECB announcement three days earlier. The right column of Figure 11 displays the impact of the Fed announcement on Sunday, March 15, by comparing the variables of interest from Friday, March 13 (before the announcement) to the following trading day, Monday, March 16. The figure indicates that the value of the underlying decreased by nearly 0.1 log points (approximately 10%), and the implied volatility increased by 16 pp, temporarily exceeding 20 pp. The downside left-tail risk, as measured by the price of far OTM put options, decreased by more than 0.5 log points (approximately 50%) on the bid side compared with the corresponding bid price at the end of trading on Friday March 13. Before interpreting this change, one has to keep in mind that the tenor of the considered puts decreased from 7 days on March 13 to 4 days on March 16. Because we control for the time decay of option prices (the option theta is negative and this effect is more pronounced the shorter the tenors) in the regressions, the finding that the bid and ask price of far OTM put options decreased relative to the respective price during the pre-event window suggests a decrease in downside left-tail risk.

The second panel in the right column of Figure 11 shows that the log ask price of far OTM put options decreased less than the log bid price. The stronger response of the bid than the ask price implies that the unexpected component of the Fed decision on March 15 increased the spread for far OTM put options and thus reduced their liquidity.

The bottom panels of the right column in Figure 11 show that both the spread and the market depth for put options with a tenor between 10 and 45 days and standardized moneyness in the interval $[-1, 0]$ were quite volatile during the trading day. The spread and the market depth fluctuated substantially already prior to the Fed's announcement. Relative to the shaded pre-event period, the spread did not change much in the shaded post-event period and the market depth increased.



Sources: Eurex. *Notes:* The dashed vertical lines illustrate the time of the monetary policy announcement, and also separates the respective trading days in the left panels. The blue shaded areas illustrate the pre- and post-event windows, on which the estimates in the main text are based. The effect on tail risk is based on puts with short tenor between 1 and 14 days and a moneyness of −2.5 (or a moneyness of −1 for March 18-20 as discussed in the main text). The implied volatility is computed based on ATM options with a tenor of 45 days, averaged across puts and calls. The figure displays the coefficients γ_i of the estimated specification (1). Elasticities on the ask and bid side are both in absolute terms so that a smaller value implies less market depth. The effect on spreads and elasticities is reported for put options with a tenor between 10 and 45 days and a standardized moneyness $[-1, 0]$. The benchmark interval is 10:00-10:45 hrs on March 18 (left column) and March 23 (right column). The coefficient for each 45-minute interval is depicted in the figures at the end of the respective interval.

Figure 13: The effect of the monetary-policy announcements on March 18 and 23 on option price states and option market liquidity

F.4 Intraday evidence for March 18-20, 2020

So far, we have presented the results on the effects of two monetary policy decisions, whose unexpected component decreased the value of the underlying (the EURO STOXX 50 index) and increased the volatility. We now turn to two monetary policy decisions which contributed to the turnaround in the pandemic by increasing the value of the underlying and reducing the volatility.

The top panels in the left column of Figure 13 show the changes of the value of the underlying, implied volatility, and tail risk after the announcement of the PEPP by the ECB in the evening of March 18. The bottom panels in the left column of Figure 13 illustrate the corresponding effect on liquidity. We include both March 19 and 20 for gauging the effect because the outcomes of interest display interesting changes for both of these trading days that followed the ECB's announcement. Specifically, our estimates show that the PEPP initially had little impact on option markets. It took until March 20 for the value of the underlying to increase by 8% and the volatility to decrease by 16 pp. The tail risk decreased significantly starting in the afternoon on March 19. The log price decreased by about 0.1 log points in the post-event window on March 20 relative to the pre-event window. The bottom panels in the left column of Figure 13 show that market depth decreased somewhat on March 19 and March 20 relative to the pre-event window, but overall there has been no clear-cut effect on liquidity of slightly OTM put options with a tenor between 10 and 45 days after the ECB's PEPP announcement.

Because we consider two-day time windows, we cannot exclude that other events that occurred on March 19 may have contributed to the observed changes beyond the ECB's announcement on March 18. After investigating additional events within this time frame, we wish to discuss the following two occurrences. The Fed offered additional liquidity arrangements to foreign central banks on March 19 at 14:00 hrs (CET) and, concerning fiscal policy, a preliminary agreement on the CARES act was announced in the U.S. after trading hours in Europe on March 19. The latter event is unlikely to have contributed to the positive trends in European markets because the day-to-day returns of the Dow Jones 30 Industrial on March 19 and March 20 were 0.94% and −4.65%, respectively, whereas the daily returns of the EURO STOXX 50 index were 2.82% and 3.78%. Concerning the Fed announcement on March 19, we do not detect an effect of this event on impact in the left column of Figure 13, i.e., at 14 hrs on March 19, but for a possibly very short-lived effect on the spread.

It is also noteworthy that March 20 was one of the four days in 2020 marked by triple witching, indicating the simultaneous expiration of stock options, index futures, and index options contracts. Although it is not obvious how triple witching should affect the estimated effects of the monetary policy decision, trading activity typically peaks before and on triple witching days. Figure 2 displays the trading volume during our sample period, highlighting the significant trading activity around the triple witching days of March 20 and June 19.

F.5 Intraday evidence for March 23, 2020

Qualitatively, the Fed's announcement on March 23 had effects similar to those observed from March 18-20, by increasing the value of the underlying and reducing volatility. However, liquidity in the option markets decreased more markedly after the Fed's announcement on March 23.

The top panels in the right column of Figure 13 show that the Fed announcement on March 23 increased the value of the underlying by 2%, decreased the implied volatility by 3 pp, and also decreased downside left-tail risk. The bid-ask spread for far OTM puts decreased, indicating more liquidity of far OTM put options.

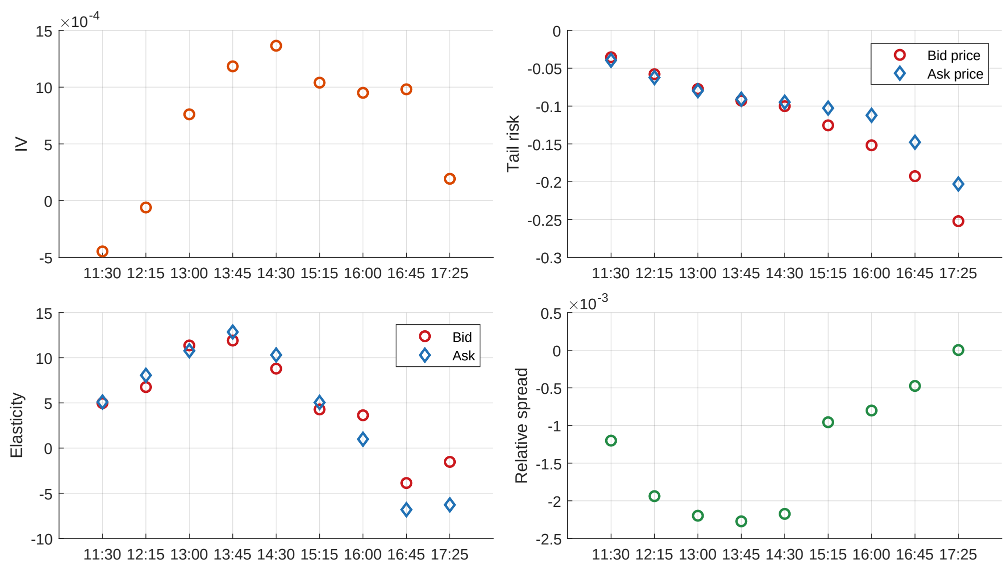
The bottom panels in the right column of Figure 13 show that the liquidity of the slightly OTM options decreased after the Fed's decision, where the spread increased up to 1.5 pp and the market depth fell by more than 100 pp in the post-event window.

F.6 Intraday patterns on non-event days

We control for typical intraday effects in our estimations. In terms of the regression specification in (1), these effects are captured by the terms $\delta_i D_{it}^{(5)}$. We report the average coefficient estimates for these effects for the four events discussed above (March 12, 15, 18 and 23), reporting the estimates for the same 45-minute intervals as in Figures 11 and 13 and using the same benchmark interval 10:00-10:45 hrs.

Figure 14 illustrates that both liquidity and volatility typically peak in the middle of the trading day, although the typical intraday effects are quantitatively minor. Between 13:00 and 15:00 hrs, volatility is usually $0.1 - 0.15$ percentage points (pp) higher, the spread is 0.2 pp lower, and market depth increases by 10 pp.

The price of far OTM options, used to measure tail risk, decreases over the trading day by $0.2 - 0.25$ log points. The bid price drops more sharply than the ask price as trading ends, widening the spread for far OTM options. Hence, the findings in Figure 14 highlight that it is necessary to account for typical intraday patterns in our analysis, especially for tail risk estimates.



Sources: Eurex. *Notes:* The effect on tail risk is based on puts with short tenor between 1 and 14 days and a moneyness of −2.5 (or a moneyness of −1 for March 18-20 as discussed in the main text). The implied volatility is computed based on ATM options with a tenor of 45 days, averaged across puts and calls. Elasticities on the ask and bid side are both in absolute terms so that a smaller value implies less market depth. The intraday patterns for spreads and elasticities are reported for put options with a tenor between 10 and 45 days and a standardized moneyness $[-1, 0]$. The figure is based on the coefficients δ_i of the estimated specification (1), averaged across the specifications estimated for the monetary policy events on March 12, 15, 18, and 23, and aggregated to the same 45-minute time intervals as in Figures 11 and 13. The benchmark interval is 10:00-10:45 hrs. The coefficient for each 45-minute interval is depicted in the figures at the end of the respective interval.

Figure 14: Intraday patterns on non-event days

G Robustness and the effects of other events

G.1 Robustness

Table 8: Robustness check accounting for calendar-week effects.

Event date	IV	Tail risk: Bid price	Tail risk: Ask price	Relative spread	Elasticity: Bid	Elasticity: Ask	Hedging costs: Change in euro	Hedging costs: Change in %
March 12	0.063	1.379	1.003	0.021	−60.3	−71.4	5,672	15.2
March 18/19	0.005	−0.035	0.035	−0.001	−37.9	−24.7	1,005	2.1
March 18/20	−0.160	−0.082	−0.063	−0.001	−25.1	2.8	−9,771	−20.5
March 23	−0.033	−0.099	−0.162	0.005	−56.2	−48.5	3,506	−8.9

Notes: See the notes of Tables 1 and 3. Compared with Table 1, we report the effect on the spread and elasticity only for slightly OTM puts for brevity. The effect on the cost of hedging is computed for options with tenor in the interval [10, 365], analogous to columns 1 and 2 in Table 3.

As a robustness check, we control for calendar-week effects to assess whether other week-specific effects confound our results. We can control for calendar-week effects without calendar-week dummies absorbing (part of) the effect triggered by the policy decision if the event window does not include days of more than one calendar week. Table 8 thus reports the results of the robustness check for the events on March 12, 18/19, 18/20 and 23 but not for the event window March 13/16, which includes days of two calendar weeks. For parsimony, we report the effects on the spread and elasticity only for puts slightly OTM. The results in Table 8 show that controlling for calendar-week effects does not change our main findings. For some events, the similarity of the results is such that the quantitative effects cannot be distinguished from those reported in the main tables at the reported precision.

G.2 The effects of further events in comparison to the main events

Concerning the effect of other events during the sample period on the option market and hedging costs, we estimate the effect of further monetary policy decisions and announcements via press releases by the ECB and the Fed during the sample period. For comparison, we also analyze the effect of fiscal policy decisions of the German govern-

Table 9: The effect of further events in comparison with the main events.

Event date	Underlying level	IV	Tail risk		Relative spread	Elasticity		Hedging costs	
			Bid price	Ask price		Bid	Ask	Change in euro	Change in %
ECB									
Decisions									
January 23	−0.006	0.005	0.120	0.056	0.001	−14.2	5.5	788	6.1
March 12	−0.054	0.063	1.069	0.787	0.021	−60.3	−71.4	5,422	11.6
March 18/19	−0.001	−0.001	−0.026	0.056	−0.001	−37.3	−23.4	86	0.1
March 18/20	0.078	−0.164	−0.083	−0.052	−0.001	−24.4	3.5	−11,990	−19.8
April 30	−0.018	0.016	−0.036	0.114	0.001	−12.9	15.9	2,610	10.1
June 4	0.005	−0.014	−0.616	−0.457	0.003	−28.3	−24.6	−1,604	−6.3
Announcements									
March 20	0.000	−0.034	0.148	0.181	0.000	−5.0	−1.5	−4,431	−8.4
April 7/8	−0.018	0.015	0.269	0.150	−0.006	−18.6	0.0	521	1.4
Fed									
Decisions									
March 3	0.000	−0.004	−0.177	−0.069	0.027	−122.2	−117.3	−827	−3.2
March 13/16	−0.085	0.162	−0.618	−0.219	0.000	47.7	34.3	10,639	18.8
March 19	0.007	−0.008	−0.281	−0.012	0.002	7.3	15.6	−696	−1.1
March 23	0.018	−0.033	−0.068	−0.138	0.005	−56.2	−48.5	−4,242	−8.3
March 31	−0.006	−0.013	−0.121	−0.118	0.002	27.9	9.4	−1,580	−3.8
April 29/30	0.006	0.000	−0.319	−0.352	−0.003	22.9	0.2	1,789	7.0
June 10/11	−0.027	0.011	0.076	0.129	−0.001	8.9	63.8	108	0.4
Announcements									
March 17	0.040	−0.098	−0.684	−0.229	0.018	−57.5	−62.3	−9,508	−14.6
March 17/18	−0.042	0.036	1.341	0.569	−0.012	29.1	40.3	4,287	7.5
April 9	0.016	−0.004	−0.103	−0.114	0.002	−34.6	−17.3	−336	−0.9
April30/May4	−0.040	0.195	0.266	0.043	0.000	−33.7	−7.4	18,651	66.0
Fiscal decisions									
March 13	0.017	0.006	0.175	0.125	0.017	−58.3	−59.2	830	1.7
March 19/20	0.070	−0.145	−0.010	0.003	0.001	2.2	1.8	−7,936	−13.2
April 9/15	−0.010	−0.008	−0.205	−0.100	0.005	−6.7	−50.9	−5	0.0
April 23/24	−0.015	0.000	0.146	0.157	−0.001	9.1	−2.9	290	0.9
May 18	0.015	−0.011	−0.036	−0.092	0.003	3.6	−3.5	−1.473	−5.2
Other events									
March 11/12	−0.062	0.061	0.311	0.239	0.005	−38.7	−35.7	−144	−0.3
May 5	−0.008	0.014	0.315	0.308	0.004	−42.3	−18.8	1,703	5.5

Notes: The main events on which we focus in the main text are in bold font. The color scheme is analogous to Table 1 with red meaning more turbulent markets with worse fundamentals (lower index valuation, higher IV, higher tail risk) and green suggests calmer markets with improved fundamentals. For the liquidity measures, red represents lower liquidity (wider spreads, lower market depth), while green stands for higher liquidity (lower spreads, more market depth). For the effects on liquidity, we report only the effects on the spread and the elasticities on the bid and ask side for slightly OTM puts, for parsimony. Under the header 'Other events' we include the WHO declaring the pandemic and Trump's travel ban on March 11, and the ruling of the German constitutional court on the ECB's decisions on May 5. See also the notes to Tables 1 and 3, and their discussion in the main text, for further details.

ment on March 13, the U.S. government on March 19 and by the EU on April 9, 23/24, and May 18. We further analyze the effect of two other salient events: the WHO declaring the pandemic and Trump's travel ban on March 11, and the ruling of the German constitutional court on the ECB's decisions on May 5.

For the effects on liquidity, we report only the effects on the spread and the elasticities on the bid and ask side for slightly OTM puts, for parsimony. We distinguish dates with monetary policy decisions from dates with announcements (press releases) which may be considered less salient and thus are usually analyzed less in the literature. Note that the announcements of the ECB on March 20 and the decision of the Fed on March 19 also are part of the event windows after the ECB's PEPP decision so that it is less clear whether the estimated effect can be attributed to the announcement or whether it caused (at least partly) by the previous PEPP decision. Thus, although we report the estimated effect if we consider these announcements in isolation, we do not interpret the respective effects further.

Table 9 summarizes the effects of the events. Concerning other monetary policy decisions during the sample period, we find that the ECB's decisions on April 30 and June 4 had significant effects on hedging costs, which are however somewhat smaller in absolute size in comparison to the huge effects estimated for the decisions on March 12 and March 18/20. On April 30, the ECB announced further liquidity provision measures, such as the pandemic emergency longer-term refinancing operations (PELTRO). This increased the implied volatility, the spread, and thus also the hedging cost. On June 4, the ECB increased the PEPP by 600 bn which reduced volatility and also liquidity. Hedging costs decreased by an absolute amount slightly smaller than the estimated increase on April 30.

None of the further Fed's monetary policy decisions during the sample period had sizable, significant effects on hedging costs except for the press releases on March 17 and April 30. On March 17, the Fed announced during trading hours in Europe to establish a commercial paper funding facility (CPFF) to provide liquidity to households and businesses, which reduced volatility, tail risk, and hedging costs although liquidity decreased. On April 30, the Fed tried to facilitate lending to small businesses, e.g., by expanding access to the paycheck protection program liquidity facility (PPPLF). If analyzed separately, we find that this increased volatility, tail risk, and hedging cost. The

ECB's decision on the same day with similar effects, however, implies that the estimated effects may not only be attributed to the press release of the Fed after trading hours on April 30 (before the holiday on May 1) but could well be the result of lagged effects of the ECB's decision on April 30 measured on the first trading day after the press release (May 4).

Concerning the effects of fiscal policy decisions or other events, Table 9 reveals that the estimated effects on hedging cost tend to be smaller and less significant than for some monetary policy decisions. The exception is the fiscal policy announcement in the U.S. on March 19/20 if it is analyzed in isolation. As we have argued in the main text, however, the effect between March 19/20 is more likely caused by futher clarifications of the previous ECB's PEPP decision (see footnote 22) rather than by the announcement of U.S. fiscal policy after trading hours on March 19.

It is intuitive that at least some of the monetary policy decisions have larger effects than the fiscal policy decisions and the other events we analyze. The high-frequency approach of identifying policy effects works best for monetary policy, for which blackout periods prior to the policy decisions likely result in larger unanticipated policy changes. Table 9 shows that among the monetary policy decisions of the ECB and the Fed, those in March 2020 on which our main analysis has focused, had the strongest effects on option markets and hedging costs. For the other considered events, only the effect of the press release of the Fed on March 17 is of similar absolute size and not likely to be confounded by other events.